# Ship Design Decision Support for a Carbon Dioxide Constrained Future

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I, John Calleya confirm that that the work submitted in this Thesis is my own. Where information has been derived from other sources I confirm that this has been indicated in the Thesis.

# Abstract

The future may herald higher energy prices and greater regulation of shipping's greenhouse gas emissions. Especially with the introduction of the Energy Efficiency Design Index (EEDI), tools are needed to assist engineers in selecting the best solutions to meet evolving requirements for reducing fuel consumption and associated carbon dioxide ($CO_2$) emissions. To that end, a concept design tool, the Ship Impact Model (SIM), for quickly calculating the technical performance of a ship with different $CO_2$ reducing technologies at an early design stage has been developed. The basis for this model is the calculation of changes from a known baseline ship and the consideration of profitability as the main incentive for ship owners or operators to invest in technologies that reduce $CO_2$ emissions. The model and its interface with different technologies (including different energy sources) is flexible to different technology options; having been developed alongside technology reviews and design studies carried out by the partners in two different projects, "Low Carbon Shipping - A Systems Approach" majority funded by the RCUK energy programme and "Energy Technology Institute Heavy Duty Vehicle Efficiency - Marine" led by Rolls-Royce. The model has been used alongside a wider economic and logistic model of the international shipping system, the focus of which is on large cargo ships engaged in ocean-crossing trade, to potentially advise on regulation and what $CO_2$ emission reductions are possible from shipping. The Ship Impact Model (SIM) allows a large design space to be explored quickly, incorporating economic considerations at a single ship level and supporting combinations of technologies and design and operational parameters. Whilst considering that comparisons against actual ship data have been limited, the model has a high enough fidelity and accuracy to be used as a decision tool in the selection between different technologies (providing the technologies are adequately described).

# Acknowledgements

*"Don't take yourself too seriously, and take yourself as seriously as death itself. Don't worry. Worry your ass off. Have ironclad confidence, but doubt - it keeps you awake and alert. Believe you are the baddest ass in town, and, you suck!"* - Bruce Springsteen, SXSW 2012

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## Chapter 1

# Introduction

## 1.1 Shipping in a Greenhouse Gas Constrained Future

Future Greenhouse Gas (GHG) emissions may be limited either due to regulation to reduce the risk of dangerous climate change or because the high prices of conventional GHG emitting energy products, such as fossil fuels, will lead to increases in energy efficiency and substitution of alternative energy sources. The credibility for such a future scenario is derived from energy scenarios, such as that derived by the International Energy Agency [International Energy Agency, 2010].

Ship owners and operators have many existing Carbon Dioxide Reducing Measures (CRMs) to choose from because many CRMs were developed in order to reduce fuel consumption. For example, the escalation of oil prices in the early 1970s followed by distruption of supplies through various Middle East conflicts has in the past led to an appraisal of wind assistance for ship propulsion as a means of saving fuels [Clayton, 1987]. More recently the 2008-2009 economic downturn has led to ship operators taking ships out of service or slowing them down [Armstrong, 2011]. Although the motivation of slowing down ships is to maximise profit, when both fuel prices are high and freight rates are low, this particular measure can be considered an operational CRM.

The primary effect of a CRM is to reduce $CO_2$ emissions, although for a CRM to be taken up by a ship owner or operator it must be profit maximising or make it easier for the ship to meet regulation, possibly both. Although there are also many other aspects of ship design and operation to consider when deciding which CRMs to use.

### 1.1.1 Definition of CRM and CRT

Two new specific terms, defined below, have been created by the author from the need for consistent use of language when modifying ships or ship operation with the prime objective of reducing Carbon Dioxide ($CO_2$) emissions:

- *A **Carbon Dioxide Reducing Measure (CRM)** is any measure that reduces the Carbon Dioxide emissions of a ship or a fleet of ships. A CRM can be categorised as an operational measure or a Carbon Dioxide Reducing Technology (CRT). An important operational (non-technological) CRM is reducing operational speed.*
- *A **Carbon Dioxide Reducing Technology (CRT)** is any technology that can be incorporated into a ship (this could be either a retrofit or new build) that reduces the Carbon Dioxide emissions of the ship compared to the original ship design (before modification). A CRT is a type of Carbon Dioxide Reducing Measure (CRM) and can be categorised as reducing propulsion power, reducing auxiliary power or using fuel more efficiently (increasing the energy per $CO_2$ emissions, possibly by using alternative fuels to oil-based fuels).*

Balland et al. have carried out some research on air emission reduction methods, including Sulphur Oxides ($SO_x$) and Nitrogen Oxides ($NO_x$), as well as $CO_2$. In Balland's work air emission reduction methods were referred to as air emission controls [Balland et al., 2010]. The more generic term abatement options or abatement measures is also often used by work submitted to the IMOs MEPC or published elsewhere [Buhaug et al., 2009] [Det Norske Veritas and Lloyds Register, 2010] [CCC, 2011]. There has also been a clear distinction between operational and technological measures, and operational measures have been assessed as likely to have an effect quickly and technical measures as likely to take longer to show a significant impact [Buhaug et al., 2009] [Det Norske Veritas and Lloyds Register, 2010]. However, there has been no clear definition of terms, possibly due to $CO_2$ emission reduction being associated with efficiency improvement. Although interlinked, there are key differences between reducing $CO_2$ emissions, reducing fuel consumption, reducing costs and increasing efficiency.

## 1.2 Shipping System Boundaries

How the shipping system boundaries are defined requires careful consideration as this could effect the outcome, similar to a control volume in thermodynamic terms. For example, if the shipping system boundary is widened to include additional parts of the shipping system, such as ports and infrastructure, then it may be necessary to examine the source of the power provided in port for cranes, Cold Ironing, etc.

The focus of this work is on large cargo ships engaged in ocean-crossing trade, large cargo ships accounted for 89% of total gross tonnage in the world fleet in 2007 [Buhaug et al., 2009].

The operational life of a ship may account for as much as around 92% of the total life cycle $CO_2$ emissions, with the Embedded Carbon, in build and at the end of the life of a ship, being small in comparison. Although this figure is based on the environmental impact of a fishing vessel [Ellingsen et al., 2002] it is relevant to cargo ships because most ships have a long operational lifetime of typically around 30 years [Tincelin et al., 2010].

This work is also focusing on the design of individual ships and CRTs that are currently available, with a very high Technnology Readiness Level (TRL) (TRLs, as defined by NASA, give an indication of how close a technology or product is to being safely applied/used [Mankins, 2009]). This means that the shipping system boundaries that will be considered in this work are defined physically and in the near future as:

- International shipping routes.
- Operational $CO_2$ emissions from lifecycle; not considering the fuel infrastructure (how a fuel or energy source is stored, manufactured and distributed).
- At a single ship level; not considering a fleet of ships.
- Currently available sources of energy and CRTs; with a very high Technnology Readiness Level (TRL).
- New build ships; not considering retrofits.

CRTs are the focus of this work because they have higher barriers to entry to the market compared to operational CRMs; requiring consideration of ship design aspects and most profit maximising operational CRM such as weather routing and trim optimisation, can be implemented easier, with little infrastructure costs, compared to CRTs [Hochkirch and Volker, 2010].

Retrofits will not be analysed (though the ability to retrofit a CRT is sometimes considered when comparing between CRTs) because all CRTs can be considered in a new build ship but not all CRTs can be retrofitted to a older ship. New builds and retrofits are also difficult to compare, it may be necessary to know more information about the remaining life and costs associated with an older specific ship in order to assess whether a retrofit or a new build, possibly with an alternative CRT, would allow for an overall reduction in costs and improvement in performance.

## 1.3 Where Existing Studies Fail

Studies specifically looking at Carbon Dioxide Reducing Measures (CRMs) have found cost-effective reductions in $CO_2$ emissions to be in the order of 30% from the use of CRTs [Eide et al., 2009] [Det Norske Veritas, 2010b]. There are two possible improvements to analysis carried out in existing work:

- Cost is used a measure of comparison. These costs are directly linked to the CRMs being examined and do not necessarily reflect the profit of a ship owner or operator.
- A Marginal Abatement Cost Curve (MACC) is normally used to assess the $CO_2$ emission reduction potential of markets and may not be the best tool to use to compare CRMs at a single ship level or at a fleet level.

Representing the shipping sector on a single MACC, as shown in Figure 6.3, can be misleading because:

- It is assumed that the CRMs are adopted in a particular order [Eide et al., 2009] [Det Norske Veritas, 2010b], when certain CRMs could be more favourable than others depending on the region the ship is operated in, contractual obligations, as well as the ship itself.
- Only one MACC is presented, there are no insights into the significant uncertainties that are related to the cost and abatement potential estimates [Kesicki and Ekins, 2012].
- Measures are normally assessed independently to arrive at specific cost and abatement options [Kesicki and Ekins, 2012].

Using cost to compare different CRMs, including the use of MACCs, is discussed in more detail in Section 6.5.

The problem with most data on CRTs is how data is presented. Data is often given by a manufacturer wishing to sell a product to prospective ship owners and operators [Hochkirch and Volker, 2010]. The potential problems of this include:

- A lack of consideration of uncertainty (normally a single value is quoted with no error bar).
- A lack of assumptions as to how the CRT is applied, a consideration of ship design and type may have an effect on the performance of a CRT (in terms of cost as well as $CO_2$ emissions).
- A lack of onboard measurements and trial data - particularly published data.
- A lack of referencing (publishing of information on data sources).

Barriers to entry to market for a CRT are not just technical (as described above). Some CRTs may need to be considered as part of a more complex shipping system [Calleya et al., 2012]; that considers economics, operation and regulation.

### 1.3.1 Development of a new CRT selection tool

The aim of this work is to: *"Develop a tool to provide quick and coherent early stage design guidance for the selection of multiple Carbon Dioxide Reducing Technologies (CRTs) that is robust to changing operational assumptions."*

It is difficult to assure CRT performance because there will always be uncertainty when it comes to estimating the performance of ships, however it is possible to address the shortcomings of existing work and consider:

- The effect of economics, operational and regulatory considerations and what should be included within the shipping system boundaries.
- Multiple CRTs and how they interact.
- The sensitivty of CRT performance to varying design and operational assumptions; with multiple ship types, speeds and sizes.

## 1.4 Layout of Thesis

This work follows a selection process of CRMs considering the shipping system boundaries defined in section 1.2.

Chapter 2 starts the literature review, which requires a wide scope, by examing $CO_2$ emissions and their effect on the atmosphere in general and this scope narrows to look at specific detailed solutions and their assumptions, so in Chapter 7 we are considering five CRTs in combination.

There is no one solution and there are design considerations to be learned at each stage of the analysis. An ongoing summary at the end of each Chapter lists the design considerations and provides direction to the analysis in the next Chapter.

In Chapters 2 and 3 there are two main questions:

- What should be included within the shipping system (or within the bounds of the analysis)?
- What CRTs should be included in the analysis?

In the later Chapters, Chapters 4, 5, 6 and 7, the questions are more specific:

- How are CRTs likely to be selected by a ship owner and operator?
- How can we model this?

### 1.4.1 Glossary and Appendices

A Glossary is at the end of this document to provide quick definitions of the terms (and acronyms) that are used.

Appendix A and Appedix B explain two projects that the work discussed in this Thesis was used for. While "Low Carbon Shipping  A Systems Approach" (LCS) was the main source of funding the "Energy Technology Institute Heavy Duty Vehicle Efficiency - Marine" (ETI HDVE) allowed for further development and validation of this work in a slightly different context.

Appendix C provides some additional background on the developments in shipping and on the baseline ships that were considered for this study.

Appendix D provides a list of publications associated with this Thesis.

# Chapter 2

# The Wider Shipping System and Operational Carbon Dioxide Reducing Measures (CRMs)

## 2.1 The link between Population Growth, Technology, Resources and $CO_2$ Emissions

The relationship between population, resources and the environment was described well by Ehrlich and Holdren [1971]. The same problems that were presented in 1971 due to human beings living in a “epidemiological environment which deteriorates with crowding”, this “is compounded by man’s unprecedented mobility”, are relevant today [Ehrlich and Holdren, 1971].

Equation 2.1 was derived using relationships described by Ehrlich and Holdren [1971]:

$$\text{Amount of } CO_2 = f(\text{Number of People}) \times \underbrace{f(\$/\text{Number of People})}_{\text{Affluence}} \times \underbrace{f(\text{Amount of } CO_2/\$)}_{\text{Carbon Dioxide Intensity}} \tag{2.1}$$

In Equation 2.1 a function of population, affluence and intensity has been used to show the relationship is a complex one, although this is still an over-simplification. Improvements in technology can reduce the $CO_2$ intensity, a measure of how much $CO_2$ comes from a particular activity (an average $CO_2$ intensity in terms of $ is used in Equation 2.1). This reduces the overall $CO_2$ emissions. However, increasing world population and affluence can increase $CO_2$ emissions. As an example, the average unit energy consumption of a fridge freezer in the UK went down 16.2% from 1996-2005, however the total energy consumption by fridge-freezers was only reduced by 2.2% percent over the same period, partly due to increasing demand for second fridges [Mayo et al., 2006].

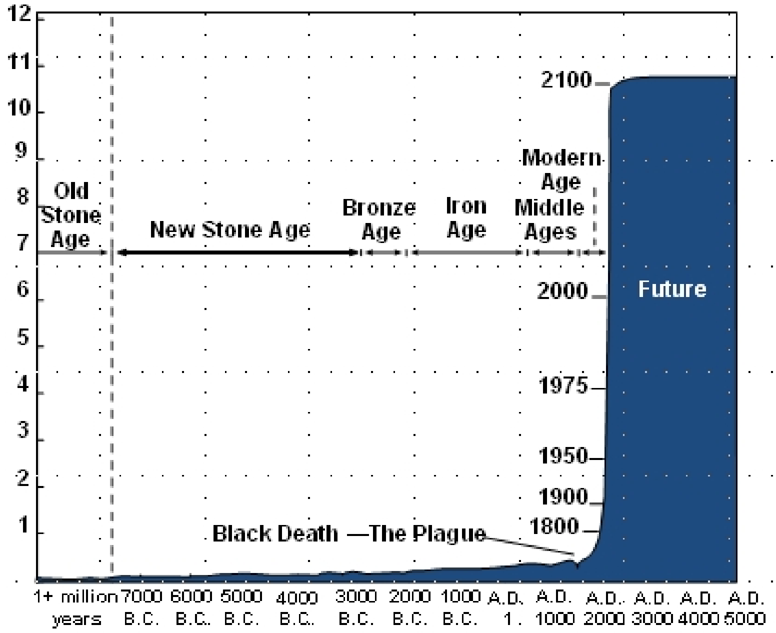



Figure 2.1: World population projections to 2100 [Joseph and McFalls, 2007] in billions of people.

Figure 2.1 shows a rapid increase in population over the past century, this may be partly due to advances in technology related to agriculture and medicine. Accounting for the current expected rate of population increase, in order to stabilise $CO_2$ emissions by 2050 the carbon intensity would have to be, assuming the most optimistic scenario with an annual population growth of 0.7% and an income growth of 1.4%, 36g$CO_2$/\$ [Jackson, 2009]. In 2007 the carbon intensity was estimated to be 768g$CO_2$/\$ [Jackson, 2009]. This means in order to stabilise $CO_2$ emissions by 2050 technology alone would have to be capable of reducing $CO_2$ emissions by at least approximately 95% compared to $CO_2$ emissions in 2007. Using technology alone may not be the solution [Huesemann and Huesemann, 2012]. In order to reduce $CO_2$ emissions and use the Earth's resources sustainably, where and how technology is employed is important. Technology also suffers from limitations in scale, lead time and cost and some technologies shift the impact rather than remove it [Ehrlich and Holdren, 1971]. Reducing population and affluence could be considered. Reducing the size of the population to keep its aggregate consumption within the carrying capacity of earth may be necessary, but there are great social and psychological barriers to even considering it [Ehrlich and Ehrlich, 2013]. It is important to note that there are also regional differences in both population and resources. Most of the poorest countries, especially in sub-Saharan Africa, are characterised by rapid growth of more than 2% per year, while most of eastern Europe, Japan, and a few western European countries are characterised by population decline [Ezeh et al., 2012].

### 2.1.1 Anthopogenic $CO_2$ Emissions

$CO_2$ is a GHG that causes a global warming effect and has a high longivity in the atmosphere, approximately 300 years [Nature, 2008]. The time in the atmosphere of $SO_x$, $NO_x$ and Particulate Matter (PM) emissions from oil-based fuels is relatively short, compared to $CO_2$ emissions. However, $SO_x$, $NO_x$ and PM emissions are toxic, may cause an irritating smell and black smoke and hence are ostensibly worse to humans than $CO_2$ emissions, which are odourless and colourless.

There is some uncertainty in exactly how much potent GHG, such as $CO_2$ and methane ($CH_4$), there is in the atmosphere and aspects affecting the Earth's temperature can also be complex. A $CO_2$ enriched atmosphere may even have some benefits [Fajer and Bazzaz, 1992]. Not all atmospheric $CO_2$ appears to remain in the atmosphere either. Less than half of the atmospheric $CO_2$ emissions have remained in the atmosphere and are likely to have been taken up by the ocean, by the land biosphere, or by a combination of both. Without this oceanic uptake, atmospheric $CO_2$ could be about 14% higher than what is currently observed, although in the far future the ocean's ability to absorb more $CO_2$ from the atmosphere is likely to be diminished [Sabine et al., 2004].

The majority of GHG emissions ($CH_4$ and $CO_2$) has historically come from agriculture [Kammen and Marino, 1993], including a significant amount of anthropogenic pre-industrial GHG. A gigatonne of $CO_2$ equivalent GHG emissions ($GtCO_2$-eq) is the unit used by the UN's Intergovernmental Panel on Climate Change (IPCC) to measure GHGs. Agriculture accounted for an estimated 5.1 to 6.1 $GtCO_2$-eq/year in 2005 (10-12% of total global anthropogenic emissions of GHGs); of which methane ($CH_4$) contributes 3.3 $GtCO_2$-eq/year [Smith et al., 2007]. In comparison, in 2007, 1054 million tonnes of $CO_2$ and 0.24 million tonnes of methane ($CH_4$) was emitted from shipping [Buhaug et al., 2009]. Accounting for methane, being 21 times more potent as a GHG gas than $CO_2$ on a per tonne basis [Sustainable Shipping, 2011], gives a total of 1.06 $GtCO_2$-eq/year from shipping. The $CO_2$ equivalent emissions from agriculture is approimately 5 times that from shipping.

Though there is some uncertaintiy in anthropogenic $CO_2$ emissions as to where, how much and possible consequences, the potential impact of human activity on the climate system is widely acknowledged [Kammen and Marino, 1993], particularly when related to fossil fuel combustion. As a potent GHG, reducing $CO_2$ emissions may be vital to stopping dangerous climate change and increasing the future quality of life on Earth.

## 2.2 Can shipping learn from the $CO_2$ emission reduction incentives and CRMs in other industries?

There are a few reasons why it is useful to look at what other industries are doing to mitigate $CO_2$ emissions:

- It is possible that some effective practices, measures or technologies for reducing $CO_2$ emissions can be used in shipping.
- Future infrastructure changes due to other industries could directly impact shipping, such as changes in fuel infrastructure and hence the availability and transport requirement of fuels.
- How other industries perform in future could offset emissions from shipping, especially if Market Based Measures (MBMs) are introduced, such as $CO_2$ emissions trading, that works across industries.
- Direct competition with other transport modes is also possible, particularly for high value cargoes, such as cars.

### 2.2.1 Automotive industry

In the automotive industry hybrid-electric cars have experienced a significant growth rate in the last 10 years [Dijk and Yarime, 2010]. The Toyota Prius was initially introduced to a niche market and even subsidised by Toyota [Dijk and Yarime, 2010]. Toyota had to take some risk in order to gain a first-mover advantage and give customers additional choice in a competitive market [Dijk and Yarime, 2010]. Many national governments have also provided subsidies on the purchase of low emission vehicles and many EU countries have implemented energy labelling schemes [Dijk and Yarime, 2010], these provide information to the customer on the fuel efficiency of a vehicle relative to other vehicles of the same size. Subsidies could be in the form of tax breaks or other benefits, such as not having to pay congestion charges.

### 2.2.2 Aviation industry

For shipping, it is possible to reduce emissions in a cost-effective way by lowering speed [Corbett et al., 2009] [Smith et al., 2011]. In aviation, lowering flight speeds can only yield significant fuel savings if engine and air frames were re-designed to realise such benefits [Lee et al., 2009]. Ultimately, more radical designs rather than step changes, such as a blended wing body and unducted-propfan engine aircraft, may be required to obtain further improvements [Lee et al., 2009]. Potential savings from aircraft design are limited because of the long-lifetime of new aircraft; for example, the fleet in 2030 will substantially comprise the best of today's technology, which has been delivering diminishing returns in terms of fuel efficiency [Lee et al., 2009].

Alternative fuels to kerosene may offer some advantages in the longer-term, it seems that liquid hydrogen is the only real alternative [Lee et al., 2009]. This would significantly reduce the operational $CO_2$ emissions to near zero, although the $CO_2$ emissions for the full lifecycle of the fuel would depend on how the fuel is manufactured, this is discussed in the next Chapter, in Sub-subsection 3.4.1.7. Usage of liquid hydrogen would require much larger airframe storage capacity, which would add weight and drag to conventional airframes [Lee et al., 2009]. Biofuels may also offer some advantages if they can be developed in sufficient quantity, economically and in compliance with the exacting performance and safety standards that are required for civil aviation. There are increasing concerns over land-usage conflicts between food and fuel production in developing nations [Lee et al., 2009]. The efficiency of aviation is improving (partly due to increasing aircraft size) but year-on-year emission rates are nonetheless increasing because passenger load factors are at a historical maximum and further significant improvements are unlikely [Lee et al., 2009].

The European Union (EU) decided to include $CO_2$ emissions from aviation in the EU Emission Trading Scheme (ETS) in 2008 [European Commission, 2009]. This was initially planned to begin in January 2012 but was subsequently postponed to 2013 and postponed much longer for airline operators outside the EU [Girardet and Spinler, 2013]. Under an ETS, the $CO_2$ costs may amount to almost 10% of kerosene costs with more incentive to improve fuel efficiency for long-haul flights because the fuel costs are a larger proportion of the overall costs of long-haul flights [Girardet and Spinler, 2013]. It is not clear how effective the ETS can be in encouraging additional investment into reducing $CO_2$ emissions; that may occur from increasing fuel costs and/or reducing demand.

### 2.2.3 Building and construction industry

The construction industry has its own methods for measuring and comparing the energy consumption of new and existing buildings [Lee and Burnett, 2008], which were developed in the 1990s. The most significant of these, in terms of reducing $CO_2$ emissions, is the Building Research Establishment Environmental Assessment Method (BREEAM) developed in the UK.

BREEAM is relevant to shipping for the following reasons [Lee and Burnett, 2008]:

- It is the first method (created in 1990) and forms the reference model for similar schemes developed in Canada, New Zealand, Norway, Singapore and Hong Kong (HK-BEAM).
- BREEAM differs from the HK-BEAM and the US Green building councils LEED in that it assesses the absolute performance to minimise the overall emissions of $CO_2$. The other schemes aim to minimise annual energy use and cost.
- It is based on actual consumption figures.

Most interestingly BREEAM also adopts an incentive crediting scheme, i.e. proportionally higher number of credits is awarded for an increase in performance level [Lee and Burnett, 2008]. Current and proposed regulatory measures in shipping for reducing $CO_2$ emissions [IMO, 2009c] [IMO, 2009b] do not incentivise bigger reductions in emissions.

### 2.2.4 Summary of reducing $CO_2$ emissions in other industries

In most industries it is normal practice to invest in incremental changes in existing technology rather than radical new designs. For example, in the automotive industry this yields a pattern in which car manufacturers continuously refine the dominant design [Dijk and Yarime, 2010].

The automotive industry may also be more competitive than aviation and shipping. An indicator of this is that there is an oligopoly of engine manufacturers in the aviation and shipping industries. From a survey of Clarksons ship database for large ships (Panamax size and above) there are only two main engine manufacturers, MAN and Wärtsilä [Clarksons, 2010] [Clarksons, 2011]. This is similar to the aviation industry, as the world aero-engine market is an oligopoly comprising of Pratt and Whitney (owned by United Technologies), General Electric, Rolls-Royce and Snecma [Braddon and Hartley, 2005].

Shipping is also similar to aviation in that $CO_2$ emission reductions from new aircraft designs and new ship designs are limited due to the long life time of aircraft and ships, in both aviation and shipping much of todays fleet will still be in use in 2030 [Lee et al., 2009] [Smith et al., 2010].

What shipping can learn from other industries:

- CRTs could be developed by considering niche markets, in shipping this could be more specialist ships where an ostensible carbon dioxide reducing reputation is important, such as a windfarm support ships or possibly a naval ship.
- Incentivising bigger $CO_2$ emission reductions (having a disproportionally higher reward for larger $CO_2$ emission reductions) could encourage further development of CRTs and the development of more radical ship designs.

A shift in fuel from kerosene to hydrogen in aviation could have a impact on shipping in terms of the availiability of hydrogen as a fuel and the need to carry hydrogen as a cargo. Aviation will compete for more high energy density liquid fuels, compared to shipping, because aircraft are much more weight sensitive than ships and aviation will be able to pay a premium for high energy density liquid fuels. The similiarities between shipping and aviation, could mean that the aviation industry may have a similar response to $CO_2$ reducing regulation to shipping. In particular, it could be useful to the shipping industry to understand how the aviation industry responds to Market Based Measures (MBMs).

## 2.3 Mitigation of Emissions from Shipping

Sections 2.1 and 2.2 examined the wider aspects of $CO_2$ emissions, from the Earth's resources to the potential $CO_2$ mitigation practices in different industries. This section considers why we need to reduce $CO_2$ emissions specifically from shipping, also considering the impact of $SO_x$ and $NO_x$ emissions. The next Section, Section 2.4, begins to examine how reductions in $CO_2$ emissions from shipping could be achieved.

According to the Second IMO Greenhouse Gas Study [Buhaug et al., 2009], shipping accounts for 3.3% of global $CO_2$ emissions, while aviation accounts for 1.9% of global $CO_2$ emissions.

The amount of emissions from shipping has been put into context by different comparisons. Such as, if global shipping was a country it would be the sixth largest producer of GHG, exceeding Germany's emissions [Oceana, 2010]. The same study indicates that the GHG emissions from shipping are approximately one and a half times those of the United Kingdom

[Oceana, 2010]. For $SO_x$ emissions, a UK newspaper made the comparison that 16 of the world's largest ships can produce "as much sulphur pollution as all the world's cars" [Pearce, 2009]. However, the largest ships carry more cargo and are more efficient, in terms of emissions per cargo carried, compared to smaller ships.

When the specific carbon dioxide emissions from shipping ($CO_2$/tonne-km) are compared against rail and road, as in Figure 2.2, shipping has lower $CO_2$ emissions per tonne-km, partly due to the bigger payloads that can be carried per journey compared to road and rail.

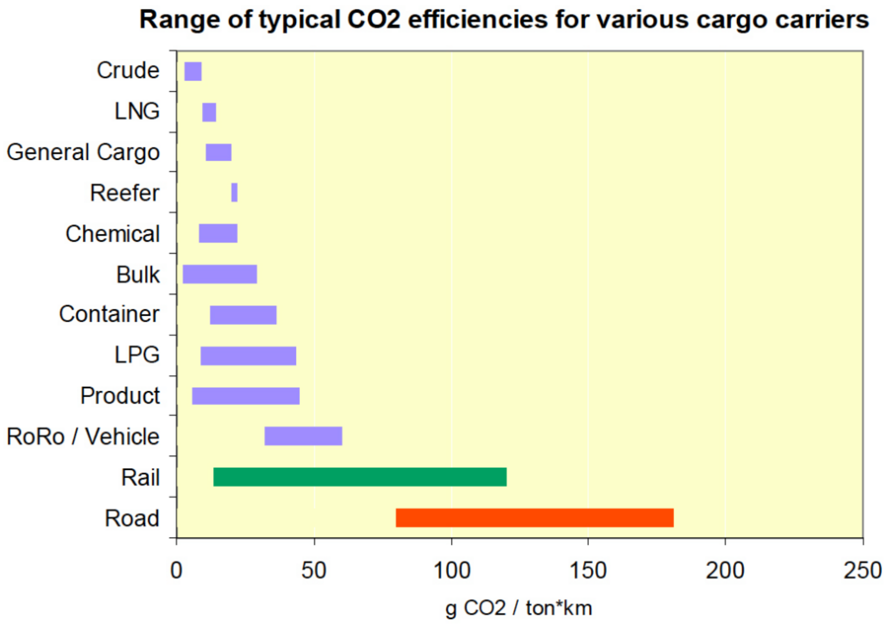



Figure 2.2: Specific $CO_2$ emissions of some common ship types [Buhaug et al., 2009].

If it can be concluded that shipping may be considered a small share of global $CO_2$ emissions and it is more efficient in terms of specific carbon dioxide emissions ($CO_2$/tonne-km) compared to other transport modes it would still be necessary to consider:

- The possible future large increase in trade due to population and economy growth while considering that shipping moves around 80 to 90% of world trade by volume [Eyring et al., 2010]. Additionally, most ships, apart from container ships, carry more dense bulk cargos (such as grain or oil) than containerised road or rail cargo. This means that if unregulated, at least a 150% increase in $CO_2$ emissions to 2050 is expected [Buhaug et al., 2009].

- The high reduction in $CO_2$ emissions that is required to limit dangerous climate change may mean that an industry or market that has the capacity to reduce $CO_2$ emissions should do so.

### 2.3.1 Why must we reduce emissions from shipping?

As well as minimising $CO_2$ emissions there are other benefits from minimising emissions from shipping. Ship emissions can have an impact on the air quality in coastal regions. About 70% of the emissions from oceangoing shipping occurs within 400 km of the coastlines along the main trade routes [Eyring et al., 2010]. See Figure 2.3. In addition, acidification of the ocean could be more significant in shallower coastal waters where shipping is concentrated [Eyring et al., 2010]. $NO_x$, $SO_x$ and PM emissions primarily cause local impacts to human health. Shipping-related PM emissions could have caused between 20,000 and 104,000 premature mortalities annually from cardiopulmonary disease and lung cancer in 2000, with a best estimate of 60,000 [Eyring et al., 2010].

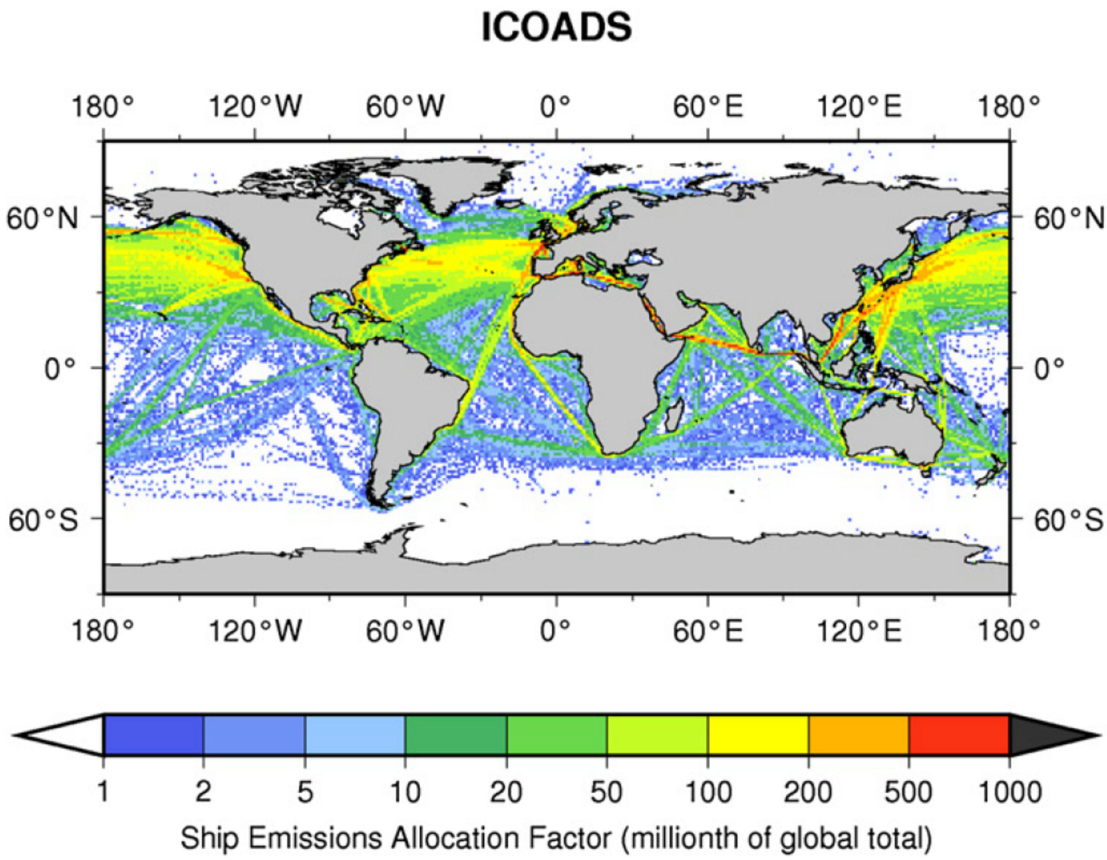



Figure 2.3: Distribution of Ship Emissions from ICOADS (International Comprehensive Ocean-Atmosphere Data Set) [Eyring et al., 2010]

Though, the local emissions shown in Figure 2.3 are not the most concerning, the most concerning impact is due to $CO_2$ remaining in the atmosphere for a long-time (in the order of centuries) and continuing to have a warming effect on the climate long after its emission [Eyring et al., 2010].

## 2.4 Incentives that Stakeholders in the Marine Industry have for reducing $CO_2$ Emissions

Shipping is built on communication and free trade [Stopford, 2009] with prices determined primaily by competition for financial profit. Stakeholders that cannot make a financial profit are unlikely to survive. Of course, there is some intevention from governments and regulatory bodies, particularly the International Maritime Organisation (IMO) (see Glossary definition), to ensure the market is fair and to address what are sometimes referred to as market failiures (such as pollution and ship safety).

As shown in Figure 2.4, initially an incentive is required that leads to a measure to reduce $CO_2$ emissions. Additionally some barriers that were not initially apparent may act against the incentives. This process occurs on multiple levels of the shipping system (such as, at the fleet level or ship level) and interactions can occur between incentives, barriers and measures.

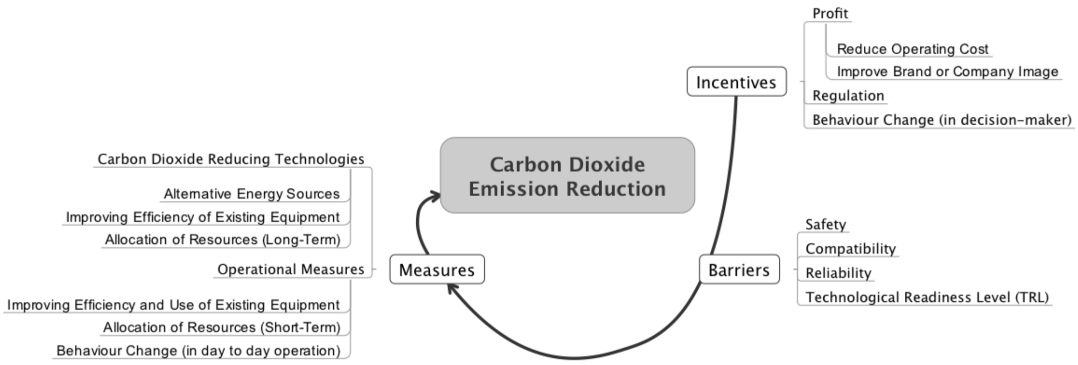



Figure 2.4: Reducing Carbon Dioxide Emissions from the perspective of the emitter.

Not all Carbon Dioxide Reducing Measures (CRMs) (shown under Measures in Figure 2.4) will cause a reduction in cost through reduced fuel consumption. Some CRMs may make it easier to meet regulations (not necessarily related to $CO_2$) or act to improve a brand or company image. For example, using natural gas as a fuel can also reduce $CO_2$ emissions by 25% compared to oil-based fuels [RINA, 2010c] due to having a lower carbon to hydrogen ratio in its chemical composition as mentioned later in Sub-subsection 3.4.1.2. Improving the brand or company image may add value and allow the company to increase their freight rate, charter costs or prices in order to make a bigger profit (this must outweigh any increased cost due to the CRM).

In order to maximise profit, the Unit Purchase Cost (UPC) and Through-Life Cost (TLC) of a CRM should be smaller than the reduction in ship operating cost due to the CRM. A reduction in ship operating cost of a CRM is normally due to reducing fuel consumption (or by changing the type of fuel), but could also be a reduction in other costs, such as port costs. In later Chapters, particularly Section 6.5, it is seen that maximising profit is much more complex than this. This is because in order to accurately measure profitability, net present value, considers both fixed and operational costs together (including costs that may vary with the deadweight of the ship, such as charter rate), for the initial examination of investment incentives we will simply consider reducing operating costs along with the following reasons to invest in CRMs:

- To reduce operating costs (likely through a reduction in fuel consumption) (in Subsection 2.4.1).
- To adhere to regulation (in Subsection 2.4.2).
- To improve a brand or company image (in Subsection 2.4.3).

There are also some some barriers to investing in CRMs from the ship owner or operators perspective, for example, safety will likely take precedence over reducing $CO_2$ emissions:

- Safety of crew and ship.
- Compatibility with existing or supporting infrastructure (for example, compatibility with port infrastructure, cold ironing or a retrofit).
- Reliability.
- Technology Readiness Level (TRL) [Mankins, 2009].
- Contractual obligations.

Some of these barriers, when considered in the opposite sense, could also act as incentives, especially when choosing between CRMs. Initially, it is necessary to consider why a ship owner, ship operator or a similar stakeholder would want to invest in CRMs at all. From a policy makers perspective there are also political barriers to adopting regulation.

### 2.4.1 Incentives to invest in a CRM to reduce operating costs (likely through a reduction in fuel consumption)

A large incentive to adopt CRMs is the high price of oil-based fuels. For shipping as a whole the price of current oil-based fuel and its usage are likely to rise due to [Buckingham, 2010]:

- Limited supply of oil and gas.
- Rising world demand for energy.
- Public and regulatory pressure on environmental emissions.

Exogenous political events in the Middle East are but one of several factors driving oil prices [Barsky and Kilian, 2004]. The potential supply of oil and gas can also change, especially with development of processes for recovering oil and gas, such as hydraulic fracturing and deeper drilling operations, in some cases as the price increases resource intensive oil and gas resources may become more financially viable. In the past, erratic fluctuations in price and supply of oil, such as the sudden escalation of oil prices in the 1970s, have led to a reappraisal of wind assistance for ship propulsion [Clayton, 1987]. Although the main reason for such work has been in order to reduce costs through reducing fuel consumption, this is a CRM.

### 2.4.2 Regulatory incentive: Current and proposed regulatory measures

From the July 2009 Marine Environment Protection Committee (MEPC) 59th session three measures were proposed, initially on a voluntary basis. The Energy Efficiency Design Index (EEDI) for new ships, the Energy Efficiency Operational Indicator (EEOI) for ships in service and the Ship Energy Efficiency Management Plan (SEEMP) (an operational performance management tool) [Warris and Bazari, 2010]. In July 2011, the EEDI and SEEMP became mandatory for new ships and all ships, respectively; coming into force in January 2013 [IMO, 2011a].

The EEDI, initially given in MEPC Circ.681 (August 2009) [IMO, 2009c] and updated in Resolution MEPC.212(63) (March 2012) [IMO, 2012a], simplifies to:

$$EEDI = \frac{\sum_{fuel=1}^{no.of fuels}(Power_f \times Consumption_f \times Carbon_f)}{Deadweight \times Speed} \tag{2.2}$$

EEDI is calculated at 75% of the main engine's Maximum Continuous Rating (MCR). Consumption is the Specific Fuel Oil Consumption (SFOC) and Carbon is a carbon factor to find the mass of the $CO_2$ emitted from the mass of the fuel. Carrying out the calculation on the top of the equation for each fuel used (for main engine power and auxiliary engine power) gives the total estimated amount of $CO_2$ emitted when a ship's main engine is operating at 75% of the main engine's MCR [IMO, 2009c] [IMO, 2012a].

A reference line is established for each ship type to which the required EEDI of MARPOL Annex VI is applicable. The calculated EEDI should be smaller than the required EEDI from the reference line. The reference line is a curve representing an average index value for a defined group of ships. IHS Fairplay database is the primary input data to for the reference line calculation [IMO, 2012b].

Following the definition in Equation 2.2, the EEDI can be reduced by:

- Decreasing resistance (decreasing power requirement).
- Generating power more efficiently (decreasing fuel consumption).
- Using a fuel with a lower carbon content.
- Using a derated main engine with a higher MCR than is current practice; considering that EEDI is calculated at 75% of the main engine's rated power.
- Increasing cargo carrying efficiency via increasing cargo (reducing power per tonne of cargo).
- Reducing ship design speed (reducing speed reduces power at a more rapid rate than the speed itself).

Though increasing the cargo capacity of a ship can reduce the EEDI of a ship, it may not make it easier for a ship to meet it's required EEDI because the maximum allowable EEDI is based upon a reference line that varies with cargo capacity and is specific to each ship type; as shown in the IMO's guidelines for the calculation of EEDI reference lines [IMO, 2012b]. The choice of ship size and speed are also influenced by economics, as well as regulation. Section 6.5 goes into shipping economics in more detail.

It is difficult to apply the EEDI across all different ship types and sizes, this is why initially not all ship types and sizes will be covered [IMO, 2009c]. For example, it is difficult to define what a capacity equivalent amount of work carried out would be for vessels that do not primarily carry cargo, such as Offshore Supply Vessels (OSVs). There is also an additional factor to account for the extra propulsion power requirements of ice-breaking ships [IMO, 2009c]. It is possible that in some cases the EEDI may work against reducing $CO_2$ emissions. As an example, classifying a ship as a heavier ice-class ship may increase the required EEDI making it easier to meet regulation.

There have been some concerns at possible design decisions where there may be a trade-off between the EEDI and safety. In particular, as the calculated EEDI is based on 75% of the rated engine power, it is possible to lower the EEDI by increasing the MCR of the main engine and installing a main engine with a lower rated power than is current practice. This can be achieved by fitting a derated main engine that is designed to operate at a lower speed, although expensive and heavier, this would allow the main engine to operate at 100% MCR continuously with no engine margin and would reduce the EEDI [Kristensen, 2010]. This would also mean reducing the engine margin and/or the sea margin, which allow for a deterioration in ship speed in bad weather and due to fouling and wear. This may make the ship underpowered in adverse weather conditions and, potentially, emit more $CO_2$ for the same speed [IMO, 2010]. Smaller sea margins for bad weather or delays could also be expensive if canal passages or berth times are missed.

The EEDI only applies to new ships. The EEOI is a operational measure defined as the ratio of mass of $CO_2$ emitted per unit of transport work [IMO, 2009b]:

$$EEOI = \frac{\sum_{fuel=1}^{no.of fuels}(Consumption_f \times Carbon_f)}{Payload \times Distance} \tag{2.3}$$

EEOI is calculated per voyage and then averaged over a number of voyages.

Compared to the EEDI, for the EEOI the fuel consumption and cargo tonnage is representative of the work done for that journey rather than the designed fuel consumption and cargo carrying capacity of the ship. This also means that for some ships the EEOI may vary significantly between voyages (for example, tankers may have voyages in ballast). The type of contract the ship is on and how the ship is chartered may also cause significant variations in the EEOI between voyages. The EEOI has an advantage in that it can be adopted at short notice with existing ships (although it is currently voluntary).

The EEOI may be harder to regulate compared to the EEDI, which can be checked when the ship is classified, but it can give a better indication of the $CO_2$ emissions of a ship because it uses actual fuel consumption figures. The IMO also laid out plans for a SEEMP, which is a tool that is likely to be used alongside the EEOI to establish mechanisms, such as a measurement system, for a company and/or a ship to improve the energy efficiency of a ships operation [IMO, 2009a]. Most shipping operators are likely to already have similar initiatives to the EEOI and SEEMP already employed because they reduce fuel consumption, and hence operating costs, and the implementation costs are small.

There has been some discussion at the IMO on MBMs [IMO, 2011b]. In theory, Emission Trading Schemes (ETSs) can reduce the costs of reducing $CO_2$ emissions by allowing the market to find the cheapest way to reduce emissions. However, ETSs do not encourage $CO_2$ emissions to be reduced wherever there is the capacity for the reduction of $CO_2$ emissions, some companies would rather pay than reduce their $CO_2$ emissions, especially if the price of emitting (or for $CO_2$ credits) is low.

#### 2.4.2.1 Why does international regulation take so long?

The introduction of the EEDI in January 2013 as agreed at the 62nd MEPC in July 2011 is a step towards reducing $CO_2$ emissions [IMO, 2011a]. This is the first international agreement on $CO_2$ emissions. However, there is no regulation in place to directly measure and report $CO_2$ emissions (and possibly reward low EEOI) while at sea. It could be possible to achieve this through a strengthened bunker delivery note. The current bunker delivery note can be inaccurate as it requires flow meters to be calibrated accurately and mis-reporting may be possible [European Commission, 2013a].

'The Kyoto Protocol is seen as an important first step towards a truly global emission reduction regime that will stabilise GHG emissions, and provides the essential architecture for any future international agreement on climate change' [UNFCCC, 2013]. Shipping was exempt from the first commitment period of the Kyoto Protocol and continues to be exempt from the second commitment period [Ritchie, 2010] [Warris, 2012a].

Technically the decisions made in the United Nations Framework Convention on Climate Change (UNFCCC) supersede those made in the IMO, although the IMO member states are also signatories to the UNFCCC. This means that there is some dissension over how much responsibility the IMO should be given, the IMO is invited to co-operate with the UNFCCC and consider feasible GHG reduction strategies [Warris and Bazari, 2010]. The current stance of the UNFCCC as outlined by the Kyoto Protocol and unchanged in the second commitment period is that shipping; "shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively" [UNFCCC, 2012].

Regulations to reduce GHG emissions can potentially have an impact on economic growth, conversley the economic and financial downturn of 2008 meant that production fell in Spain and Spain exceeded its $CO_2$ emissions target set by the Kyoto Protocol for the period up until 2012 by only 0.9% [Zafrilla et al., 2012]. Part of the problem in agreeing on international regulation for GHG emissions is that climate change exacerbates the challenges of growth and development. Developing countries cannot follow the carbon-intensive development path that high-income countries did. A development path in which developing countries avoid being locked into a high-carbon, low-competitiveness future will require substantial efforts on the part of both high-income and low-income countries [Hamilton and Fay, 2009].

Though it is important to consider how to raise an adaptation fund to support less developed countries in managing the impact of climate change the expectation is that the IMO would have the regulatory responsibility for international marine bunker fuels. This means that the IMO principle of "equal treatment of all ships" is upheld avoiding the UNFCCC principle of common but differentiated rules and responsibilities [Warris and Bazari, 2010]. Previous agreements at the UNFCCC recognise the pledge of \$30 billion from 2010 to 2012 from industrialised countries to support the reduction of climate change in the developing world and the intention to raise \$100 billion per year by 2020 [Ritchie, 2010]. There was a risk of shipping being used to help raise money to support the reduction of climate change in the developing world, this has since subsided with no mention of shipping in long-term finance plans at Doha in 2012 [Warris, 2012a].

The IMO was late in including $CO_2$ emissions into MARPOL Annex VI, in the early to mid 1990's $CO_2$ emissions were discussed and not included because of the difficulty in obtaining agreement on the measures to be adopted to control $NO_x$ and $SO_x$ emissions, also there is often an inverse relationship between $NO_x$ emissions and energy efficiency (and consequently $CO_2$ emissions) [Reynolds, 2011]. The slow progress at the UNFCCC means that the IMO considered issues such as technology transfer, to assist developing countries, before the UNFCCC [Warris, 2012b]. There are two main themes; technology transfer as envisaged by the UNFCCC and the relationship between technology transfer and regulation, such as the EEDI and SEEMP [Warris, 2012b].

Meanwhile, the European Comission is making its first steps to include MBMs in shipping. In June 2013 the European Comission put forward a proposal to monitor and report $CO_2$ emissions for all ships calling at European Union (EU) ports over 5000 gross tonnes to come into effect in January 2018 [European Commission, 2013b]. As well as including all voyages within the EU the monitoring of voyages to or from EU ports from the previous non-EU port to next non-EU report, respectively, are also included [European Commission, 2013b]. This is a pre-requisite for any MBM or efficiency standard, whether applied at EU level or globally, the European Commission's clear preference is for measures to be taken at a global level [European Commission, 2013b]. if this proposal goes ahead as suggested it may take at least approximately 5 years to apply any MBMs or efficiency standard (this is assuming the same time frame between the date of the proposal and when it comes into effect), unless the IMO is quicker to implement its own efficiency standard.

There are many different political factors and organisations involved that make international negotiations slow. Due to the slow progress of international negotiations it is necessary to continue to anticipate increased regulation at regional level as well as IMO level [Warris and Bazari, 2010]. The main regional emission legislation, under the IMO agreement MARPOL Annex VI, is that countries can apply to set up an Emission Control Area (ECA). After the United States and Canada, in 2009, submitted a proposal to set up an ECA off the coast of both countries this was the third such geographical area to be designated as a ECA and the first to include $NO_x$. However ECAs do not include include $CO_2$ emissions, $NO_x$, $SO_x$ and PM can be covered by an ECA [Sustainable Shipping, 2009]. If operators have to consider different regulations in different regions it will make things more difficult for them. However regional legislation may develop into international legislation.

#### 2.4.2.2 A UK perspective on regulation

In the United Kingdom, the Committee on Climate Change (CCC) produced an initial report in 2008 containing recommendations on the UK's 2050 emissions reduction target [CCC, 2008]. Initially, the CCC concluded that including international shipping emissions within the UK budget system was inappropriate because allocating global shipping emissions to the national level is difficult and a number of allocation methodologies, such as using bunker fuel sales or freight tonne loaded basis, give vastly different results [CCC, 2008].

A later, more in depth, review of shipping by the CCC mentioned "That one reasonable answer is that the UK should be responsible for all of the shipping emissions involved in the transfer of cargos between the UK and its trading partners" [CCC, 2011]. Although better data is required about the current $CO_2$ emissions from shipping, shipping should be included in the UK emissions reduction targets, this includes up to 18 million tonnes of $CO_2$ from shipping in a target of 160 million tonnes of $CO_2$ by 2050 [CCC, 2011]. The CCC made the conclusion that shipping should be included in the UK's emission reduction target based on the opinion that there is a "Significant amount of cost-effective abatement potential in shipping" and this could reduce "Economy-wide costs of abatement", and gave the recommendation that the "Government should argue for international policies going beyond what has currently been agreed by the IMO" [CCC, 2011]. Assuming that shipping does have a "Significant amount of cost-effective abatement potential", by including shipping in UK targets and arguing for international policies, the UK could then both decrease the required emission reduction for non-shipping emissions by up to 18 million tonnes of $CO_2$ and possibly get the international shipping community, represented by the IMO, to fund and implement $CO_2$ abatement policies and measures in shipping.

### 2.4.3 Incentive to improve a brand or company image

Shipping stakeholders may be concerned about their environmental image. For example, environmental image can be important to energy related industries, such as oil and gas companies, or renewable energy companies. Although the main incentive is still likely to be cost or regulation, especially when transiting ECAs or operating in arctic regions, there is a niche market of offshore supply vessels that use LNG as a fuel [Offshore Magazine, 2008]. Other niches such as wind farm support ships or inland ships may do more to improve their environmental image. The emission controls on inland ships may be more severe because of their proximity to towns and cities [RINA, 2010c].

Businesses (associated with brands) may also put pressure on their supply chain to be more sustainable. The Clean Cargo Working Group (CCWG) represents global businesses who are interested in the sustainability of their supply chain. The CCWG uses an equation to calculate $CO_2$/TEU-km [CCWG, 2011]. Measuring $CO_2$ emissions per TEU may be a useful index for the businesses involved, however the emissions directly associated with a specific TEU will vary because the mass of individual TEU containers can vary significantly according to what the container is carrying. The brands in the CCWG are well-known and advertising these brands as sustainable can add value and may increase profits for the businesses involved, as some customers may choose sustainable brands over non-sustainable brands, even at a higher price.

Shipping companies sometimes develop concept designs, such as the Wallenius Wilhelmsen 'Orcelle' or the NYK 'Super Eco Ship 2030' [Wallenius Wilhelmsen, 2005] [NYK Group, 2010]. Many of the concept designs produced to date have either focussed on the maximum practical reduction of emissions achieved using, existing, mature technology or how emissions from a ship can be reduced to zero. This does not necessary represent the approach used by prospective ship owners when specifying new tonnage [Calleya et al., 2012]. These concept designs are sometimes used as way to improve a shipping companies Corporate Social Responsibility (CSR) image, although it is possible they may prompt development of more sustainable ships.

## 2.5 Carbon Dioxide Reducing Measures (CRMs)

Depending on the incentive that is in place (as discussed in Section 2.4) there are a number of ways to reduce $CO_2$ emissions from shipping. As shown in Figure 2.5, in the first instance CRMs can be divided into operational measures (in the short-term) and technical measures (CRTs) (in the long-term) [Det Norske Veritas and Lloyds Register, 2010]. CRTs take longer to show a significant impact (20-30 years), partly because these measures can be better exploited by new build ships [Det Norske Veritas and Lloyds Register, 2010]. Additionally the current global fleet is comparatively young due to the boom in the industry over the first ten years of this century [Smith et al., 2010]. Short-term measures may also have the added benefit in that they can be applied very quickly to changing market conditions.

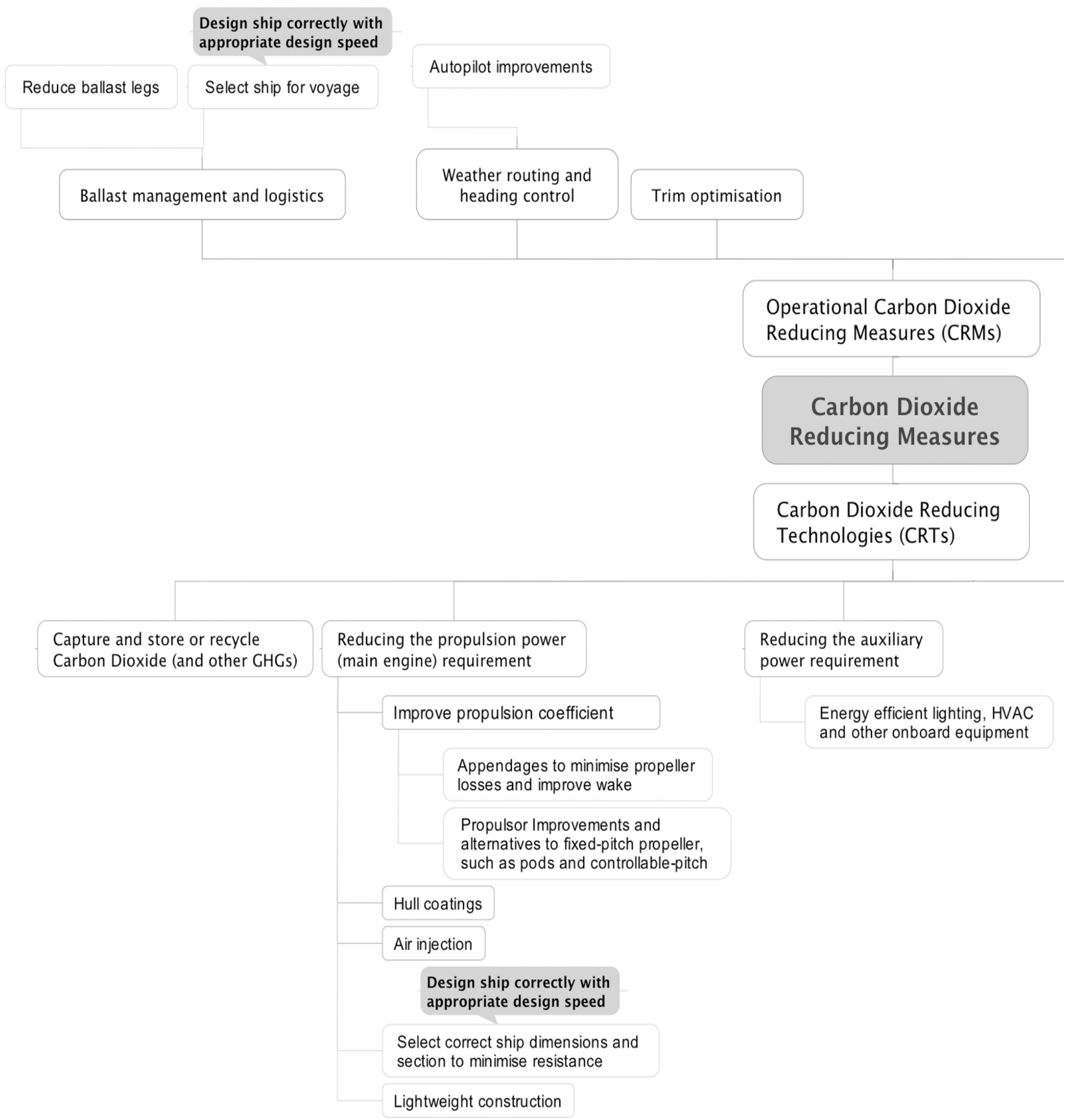
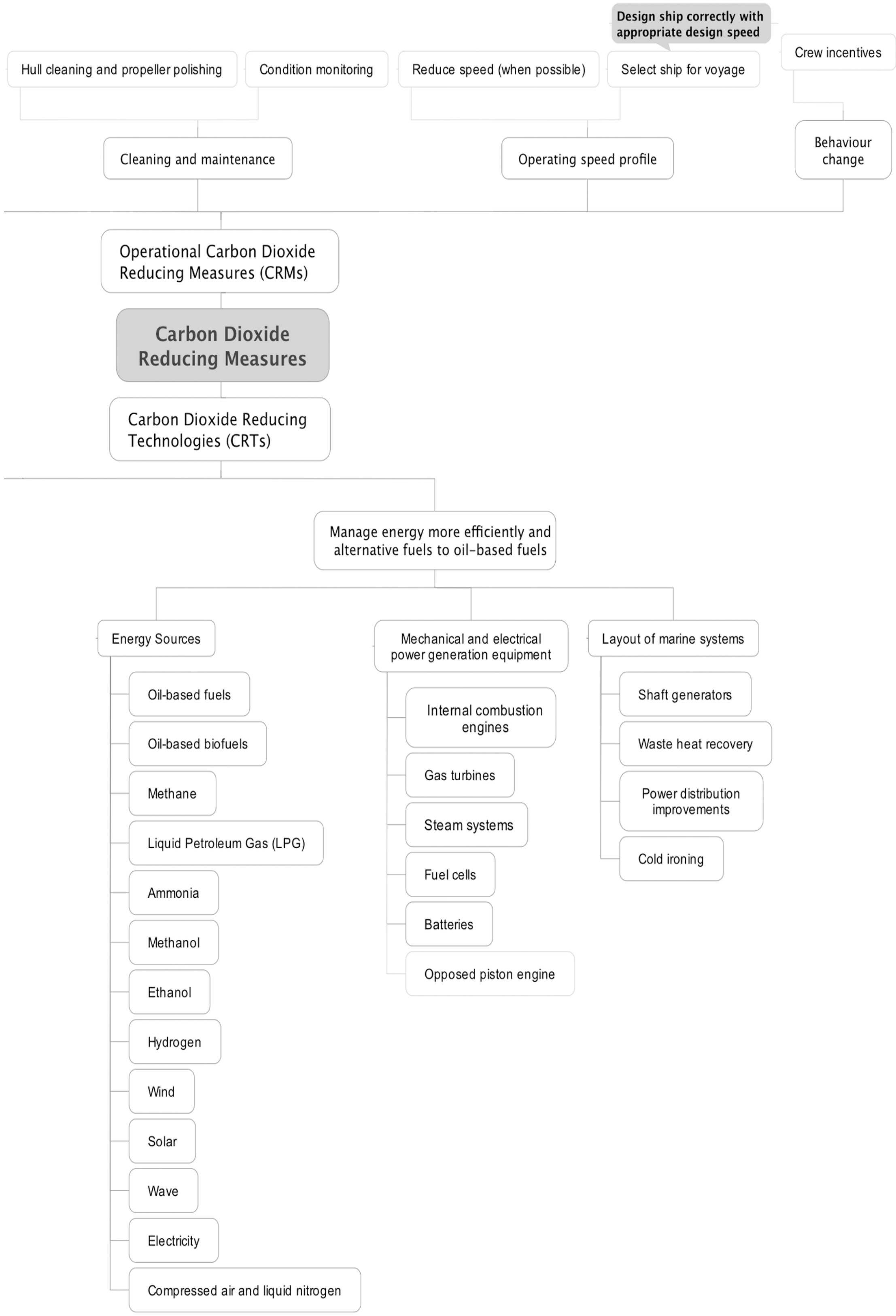



Figure 2.5: Two page diagram summarising the Carbon Dioxide Reducing Measures (CRMs) that are discussed in Section 2.6 and Chapter 3. The CRTs at the bottom of the diagram are in the scope of this work, as defined in Section 1.2. The operational CRMs can effect CRTs.


Design ship correctly with appropriate design speed
Hull cleaning and propeller polishing
Condition monitoring
Reduce speed (when possible)
Select ship for voyage
Crew incentives
Cleaning and maintenance
Operating speed profile
Behaviour change
Operational Carbon Dioxide Reducing Measures (CRMs)
Carbon Dioxide Reducing Measures
Carbon Dioxide Reducing Technologies (CRTs)
Manage energy more efficiently and alternative fuels to oil-based fuels
Energy Sources
Mechanical and electrical power generation equipment
Layout of marine systems
Oil-based fuels
Oil-based biofuels
Methane
Liquid Petroleum Gas (LPG)
Ammonia
Methanol
Ethanol
Hydrogen
Wind
Solar
Wave
Electricity
Compressed air and liquid nitrogen
Internal combustion engines
Gas turbines
Steam systems
Fuel cells
Batteries
Opposed piston engine
Shaft generators
Waste heat recovery
Power distribution improvements
Cold ironing

## 2.6 Operational Carbon Dioxide Reducing Measures (CRMs)

The Second IMO GHG study [Buhaug et al., 2009] mentions a number of operational CRMs, such as using suitable ships (that meet the cargo requirement), reducing operational speed, weather routing, trim optimisation and cleaning the hull and propeller. It is also necessary to understand how operational CRMs can be modelled on a ship and alongside CRTs. Table 2.1 gives a summary of the percentage $CO_2$ emission reductions mentioned in this Section.

### 2.6.1 Ballast management and logistics

From a technical perspective, it may be possible to reduce $CO_2$ emissions by designing the ship so it needs to carry less ballast. A ballast-free ship design [Kotinis and Sirviente, 2004] could also be used. Ballast-free ship designs are normally intended to reduce the transport of ballast water and the introduction of invasive marine species into new environment. The EEDI may also discriminate against ballast-free ships because they are likely to be less efficient at a given design speed.

From an operational perspective, it may be possible to reduce the number of ballast legs by planning voyages better. Using suitable ships (that meet the cargo requirement) can also be important [Buhaug et al., 2009]. This and other aspects of logisitics that are associated with allocating resources are outside the scope of this work, defined in Section 1.2.

### 2.6.2 Weather routing and heading control

Voyage and heading optimisation is important as the shortest distance over water does not necessarily give the lowest fuel consumption or shortest voyage time. This is an area that already has had the financial incentive to be developed because autopilots are fairly inexpensive compared to most other fuel-reducing measures, not requiring any changes to the ship. Trials have shown a 1% reduction in $CO_2$ emissions from a bulk carrier from a Japan based marine navigation company [Sustainable Shipping, 2010]. A well optimised autopilot function can remove the need for unnecessary changes in heading, reduce the energy loss in the rudder as well as reducing the distance sailed off-track. More sophisticated and GPS based autopilots can eliminate unwanted background noise caused by ship motions, by continuous identification of the ships manoeuvring characteristics against a variation of ships speed and draught, that gyroscopic autopilots would pick up. This is particularly useful in heavy weather. However, such technology requires a ship model (possibly containing manoeuvring characteristics for different speeds and draughts) that will be specific to the ship the autopilot is installed on, it may prove to be more cost-effective if employed on a class of very similar ships.

### 2.6.3 Trim optimisation

When a vessel is loaded in the design condition the ship is at a specific trim to give minimum resistance (course stability, seakeeping and propeller submergence are also important considerations). During operation, a vessel can be partially laden or in a ballast condition. Although this causes a decrease in frictional resistance compared to the design condition due to a reduced wetted surface area, residuary resistance may increase. The optimum trim angle in this operating condition will be different to the design condition. The optimum trim condition depends on the shape of the bulb and position of cut-up and transom and may change as fuel is used. For example, a container ship with a flatter upper stern section may benefit from trim by the bow to keep the bulbous bow more immersed and reduce the wetted surface area at the stern. In service a trial and error approach could be used to find the optimum trim using a shaft torsion meter to give quick results. Reductions in fuel consumption of approximately around 5% may be possible from trim optimisation [Hochkirch and Volker, 2010].

### 2.6.4 Cleaning and maintenance

The equipment and machinery should be selected and maintained in an maintenance interval that ensures the safe operation of the ship as well as to reduce the overall $CO_2$ emissions in a cost-effective way. Hull cleaning and propeller polishing are the most important aspects of cleaning and maintenance because they can have the a much larger effect on both the $CO_2$ emissions and fuel consumption compared to the maintaining of equipment. As an incentive to reduce $CO_2$ emissions the amount and interval of hull cleaning (required due to fouling) and propeller polishing that is carried out can be deduced to reduce fuel consumption for the minimum cost. For example, cleaning the propeller regularly more often than the hull could prove a cost-effective way, not requiring dry docking, to reduce $CO_2$ emissions.

Buhaug et al. [2009] stated that the appropriate choice of hull coating and hull maintenance can amount to a 5% difference in energy requirement. However, the fuel consumption of a ship at a certain time will vary due to the specific condition of the hull and propeller at any one time. In more extreme cases, the improvement in the fuel consumption of an older ship, depending on prior condition, could have a reduction in fuel (or energy) consumption of between 25% and 40% due to the surface preparation alone [Wallentin, 2011].

Cleaning and maintenance should be modelled as an operating assumption, as summarised in

Table 2.1, because it is a CRM that varies depending on how the ship is operated, although it may also depend on the ship specification and what CRTs are being used.

### 2.6.5 Operating speed profile

The power requirement of a vessel is approximately proportional to the speed cubed. This means that at higher speeds the power requirement can be reduced significantly by reducing the speed by a small amount, significantly reducing fuel consumption. When reducing the speed of existing ships, the effect of speed on resistance far outweighs both the increase in specific fuel consumption, of the engine, that occurs below around 50% MCR and other issues due to the ship operating off its design point, such as the propeller and bulbous bow not in their design conditions. If ships go slower the fleet size may also need to be increased to maintain the same fleet capacity. As $CO_2$ emissions are likely to increase linearly with increasing fleet size the overall effect of a slower bigger fleet is likely to be a reduction in operational $CO_2$ emissions.

From a technical perspective, continuous operation of engines at low load (10 to 40% MCR) requires more attention from the operator. This is because most engines were not designed to operate continuously at low load. For example, the build up of soot should be avoided and the auxiliary blowers may have to be operated continuously to reduce the exhaust gas temperature and may be subject to more wear than was anticipated when they were designed [MAN, 2009]. When operating at low engine loads, hence low speeds, journey times will also be increased.

Reducing the speed of container ships gives possible emission reductions of up to 70% when the speed is halved [Corbett et al., 2009]. The same study also estimated a fuel tax could be used to lead to average speed-related $CO_2$ emission reductions of about 20-30%. Although fleet capacity can be maintained by adding extra ships the time for a given container to reach its destination may increase [Corbett et al., 2009]. A further consideration is how slow ships can go before the cost of maintaining the relatively fixed (compared to main engine power) auxiliary power outweighs the fuel saving benefits from the main engine, due to more days at sea. Other fixed-costs, such as crew and charter costs, may also need to be considered. One analysis estimates the lowest total $CO_2$ emissions occurs between 3 and 7 knots, suggesting a large $CO_2$ emission reduction potential from speed reduction [Smith et al., 2011]. In practice, the optimum operational speed may not be achieved due to barriers that exist within the industry. Standard charter party contracts stipulate that a chartered vessel must sail at “utmost despatch” without consideration of berth availability at destination ports [Alvarez et al., 2010]. This provides the charterer an incentive to instruct the master to sail at full speed to the ports which admit vessels on a first come first serve basis [Smith et al., 2011]. "Virtual arrival" can be used to reduce a ships speed and avoid port and terminal congestion by a mutual agreement with all the parties involved [Ranheim and Hallet, 2010]. One example of this mutual speed reduction shows a reduction in $CO_2$ emissions of 27% [OCIMF and Intertanko, 2010].

### 2.6.6 Selection of operational CRMs

Table 2.1 gives a summary of the percentage $CO_2$ emission reductions mentioned in this Section. Cleaning and maintenance and operating speed profile (possibly through changing engine MCR) are two measures that should be considered in more detail alongside Carbon Dioxide Reducing Technologies (CRTs) and the ship.

| How CRM is modelled | Carbon Dioxide Reducing Measure (CRM) | Literature Review $CO_2$ reduction (if mentioned) |
|---|---|---|
| Rejected - Outside the shipping system scope (defined in Section 1.2) | Ballast management and logistics | |
| | Weather routing and heading control | 1% [Sustainable Shipping, 2010] |
| | Trim optimisation | 5% [Hochkirch and Volker, 2010] |
| Operating Assumptions | Cleaning and maintenance | 5% |
| | Operating speed profile | 20% to 30% [Corbett et al., 2009] [OCIMF and Intertanko, 2010] |

Table 2.1: Summary of Carbon Dioxide Reducing Measures (CRMs) examined in Section 2.6.

Some operational CRMs could have a bigger effect on the performance of some CRTs compared to others, for example weather routing and heading control is more important for sail assisted propulsion. In this instance, weather routing and heading control was rejected due to requiring a very wide scope of work, uncertain environmental data (such as wind and wave data) and operational data. This is something that could be addressed in future work. Trim optimisation was also rejected on the basis that an understanding of the typical operational procedure for current ships, such as the normal operating trim, is required.

The first column in Table 2.1 describes how the CRMs are modelled. In Chapter 3, Table

2.1 is updated in Table 3.2 to include CRTs, which are modelled differently to operational CRMs.

## 2.7 Behaviour Change

Rising public awareness or behaviour change towards climate change is something that could effect the $CO_2$ emissions from shipping in three different ways:

- Change in behaviour of a ship's crew, can be considered a CRM, most likely through training and incentives.
- Change in behaviour as an incentive to adopt CRMs at a ship operator or ship owner level.
- Rising public awareness of climate change could make it more important for shipping companies to ensure that they have a good environmental image.

Behaviour change by the ship owner or operator is difficult compared to behaviour change by the crew, as the prime motivation for adopting CRMs is likely to be to reduce costs rather than to reduce $CO_2$ emissions.

It is possible to incentivise the crew to reduce $CO_2$ emissions, likely through a reduction in fuel consumption. The U.S. Navy operates an incentivised shipboard energy conservation program called i-ENCON. i-ENCON considers energy conservation in all areas of operation (including equipment and auxiliary power as well as propulsion) and gives incentives to the crew to reduce fuel consumption, such as additional cash to buy new equipment and awards and recognition [U.S. Navy, 2011].

### 2.7.1 Public perception of climate change

Public perception of climate change is important, particularly when considering what is perceived to be a low $CO_2$ emission solution, or even a renewable or sustainable solution, because in some cases this may have an impact on engineering solutions. This could be more important for ships that have more contact with the public, such as passengers ships and may relate to brand or company image as an incentive to adopt Carbon Dioxide Reducing Measures (CRMs), as discussed in Subsection 2.4.3. The right messages are not always conveyed to the public [Warris, 2010]. This may be partly due to messages about climate change being conveyed to the public by the media and politicians instead of engineers or scientists [Warris and Bazari, 2010]. This can have an impact on engineering solutions. For example, wind turbines have been a fairly favourable way of producing electricity, see Figure

2.6, particularly in the UK. It is possible that this is due to wind energy being an ostensible low $CO_2$ emission energy source, however from an engineering perspective using wind energy can be impractical. Connection of large wind farms to a grid, for land applications, may cause problems in terms of power quality due to the variability of the energy extracted from the wind [Tascikaraoglu et al., 2011]. In order to rectify this, in some cases, it may be necessary to supplement wind power with conventional oil or coal based power plants that can adjust their power output according to demand.

It is apparent that it has not been clear among the UK public whether climate change is man-made or not. In the UK, a story in The Times newspaper in 2009 stated that, "41 percent agrees that it is established that climate change is largely man-made." [The Times, 2009]. A more recent article by the BBC points to a similar survey for The Times in 2012 that puts this number around the same at 42 percent [McGrath, 2013].

#### 2.7.1.1 Climate Change or Nuclear Power?

Public perception also depends on how the argument is framed and varies according to location.

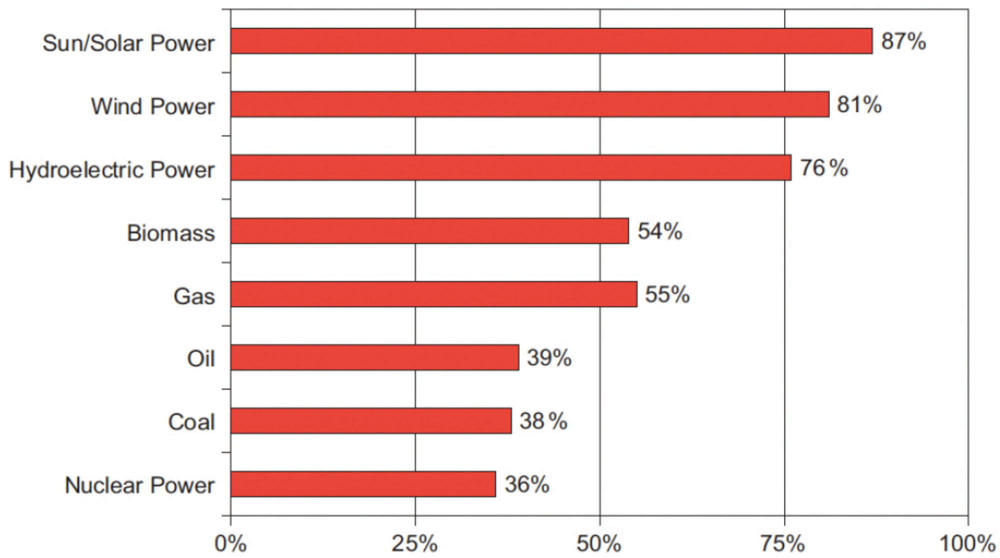



Figure 2.6: UEA/MORI Energy Survey 2005: "How favourable or unfavourable are your overall opinions or impressions of the following energy sources for producing electricity currently?" [Pidgeon et al., 2008]

Figure 2.6 shows the response to a public opinion poll on sources of energy for producing electricity. In 2005, more people were willing to accept climate change mitigation through nuclear power compared to other sources of energy. Nuclear power being seen as the lesser of two evils (this is termed reluctant acceptance) [Pidgeon et al., 2008]. Nuclear power is viewed much more positively in France, than in the UK or USA, which has extensive nuclear electricity generation capability [Pidgeon et al., 2008].

In 2011, the release of radiation from the Fukushima nuclear power station in Japan caused many governments to suspend their nuclear power projects, even when you put the event into context with the earthquake and tsunami which led to it being the direct cause of massive suffering. This is due to political decisions being made on the basis of how people feel, rather than just responding to objective measurements of risk [George, 2011].

## 2.8 Summary and Conclusions

As mentioned in Section 1.2, how the boundaries of the analysis are defined requires careful consideration. Those aspects of the shipping system that have a smaller effect on the ship design itself need to be removed from the analysis to allow more in-depth analysis on the more important aspects of the shipping system.

It is possible to summarise from Section 2.4 that reducing cost is probably the most important incentive for a ship owner or operator to invest in a CRM. This is both due to the high price of current fuel and the very slow speed at which $CO_2$ emission reducing regulation is likely to be adopted in future.

Some short-term operational CRMs, particularly those associated with allocation of resources (logistics) are not going to have a large effect on the ship design process because ship design decisions are associated with more long-term decisions. Most operational CRMs, mentioned in Section 2.6 are also likely to be already adopted onboard current ships because they are fairly easy to implement and cost effective, requiring little or no investment.

Some future changes and incentives relating to human behaviour have also been discussed; these areas are highly uncertain:

- How can other industries effect shipping in the future?
- What the regulation could be present in the future?
- How does the operation of a ship vary with changes in the crew and incentives to reduce fuel consumption?

Given the above uncertainties the ship and CRTs should be flexible to changes in operational performance, a ship may have multiple operators during its life. All aspects of how the crew uses onboard energy could be important. However a ship's operational speed profile, as discussed in Subsection 2.6.5, is likely to be the most important operational CRM. The reason why the operational speed profile is so important is because it is a link between operational, economic and technical considerations.

From looking at CRMs and the wider shipping system, those aspects of the shipping system that could have a large impact on the ship design and CRTs are:

1. Reducing cost is the main incentive to use CRMs.

2. Operational CRMs, operating speed profile and cleaning and maintenance, are important operational assumptions for CRTs.

# Chapter 3

# Review of Carbon Dioxide Reducing Technologies (CRTs)

## 3.1 Introduction to Literature Review of CRTs

It was discussed in Section 2.6 that CRMs can be split into operational Carbon Dioxide Reducing Measures (CRMs) and technical Carbon Dioxide Reducing Technologies (CRTs). As shown in Figure 2.5, CRTs can reduce $CO_2$ emissions by:

- Reducing the propulsion power requirement (in Section 3.2).
- Reducing the auxiliary power requirement (in Section 3.3).
- Managing energy more efficiently and using alternative fuels to oil-based fuels (in Section 3.4).
- Capturing and storing or recycling $CO_2$ emissions (and other GHGs) (in Section 3.5).

In this Chapter the literature review of different CRTs has a wide scope and the purpose is to estimate what $CO_2$ emission reductions are possible from different CRTs and to determine how a ship design model can be developed to incorporate different CRTs. This is summarised at the end of the Chapter in Table 3.2.

We are also considering the shipping system boundaries that have been defined to this analysis in Section 1.2; retrofits will not be analysed (though the ability to retrofit a CRT is sometimes considered when comparing between CRTs).

## 3.2 Reducing the Propulsion Power Requirement

The propulsion power requirement for a given speed can be reduced by:

- Reducing the resistance of a ship, mainly by reducing the skin-friction resistance - this is appropriate considering the lower Froude numbers of large cargo ships, compared to smaller and faster ships, that are examined in this Thesis. Resistance can be reduced by using expensive lightweight materials to decrease displacement and by making hydrodynamic changes [Hochkirch and Volker, 2010].

- Improving the propulsion efficiency.

### 3.2.1 Designing a ship for lower through-life fuel consumption

Designing a ship correctly for lower through-life fuel consumption can reduce $CO_2$ emissions. Designing a ship correctly will not be considered as a CRM because it is not a change to the ship to reduce $CO_2$ emissions but is ensuring that the ship is designed correctly before any changes to the ship are applied. This may represent future ship designs and due to the potentially large changes on the overall ship this can be analysed more accurately as a change in the baseline ship specification, rather than a modification to an existing ship.

In order to better design a ship to minimise its fuel consumption it is necessary to correctly decide the ships dimensions and section. For instance, most commercial ships have a wall-sided rectangular cross-section where a trapezoidal section with a larger draught will be better for reducing resistance [Schneekluth and Bertram, 1998]. Frequently the ship's shape has to be adapted to the cargo (as well as meeting port and canal constraints). For example, for a container ship, the usual method is to fair the ship's lines around the container load plan. However it is better to take hydrodynamically favourable ship forms and distort them linearly until all containers can be stowed [Schneekluth and Bertram, 1998]. In some areas there maybe trade-offs between an optimal design for low resistance and build costs. For example, flat plates could be easier to fabricate.

CRMs that may become less effective or not required by designing a ship with an appropriate design speed and hull form for the intented voyage are highlighted by callouts in Figure 2.5. Though the selection of the design speed will not be considered as a CRM it is an important consideration in order to maximise the $CO_2$ emission reduction potential of CRMs.

### 3.2.2 Improve propulsion coefficient

Appendages, such as using a flap rudder to reduce rudder size or using a twisted rudder can yield a 4% fuel consumption saving [Hochkirch and Volker, 2010]. Pre-swirl and post-swirl devices can be used to reduce propeller rotational losses, however gains in these areas are not cumulative [Hochkirch and Volker, 2010]. Operating in a better wake is also important although there are doubts concerning the effectiveness of wake equalising ducts [Hochkirch and Volker, 2010]. Propulsion coefficient improvements are also likely to dependent upon speed or possibly Froude number because they effect the efficiency of the hull, the propeller and the interaction between the hull and the propeller.

### 3.2.3 Hull coatings

Skin friction resistance can be reduced by applying a coating to the hull of a ship. In 2011, Nippon Paint Marine Coatings Co. Ltd. quoted a reduction in fuel consumption of 4% on a tanker when compared to 'conventional' coatings [IMarEST, 2011a]. Another coating, Intersleek 700 by International Paint, was claimed to offer a 6.4% reduction in fuel consumption [IMarEST, 2011a]. However, it is difficult to measure the performance of different coatings, the actual savings cannot be realised until after an extended period of operation. This is because as the level of fouling increases the long-term performance of different coatings may be effected in different ways. Although some paint manufacturers claim large fuel savings of around 5% to 10%, it depends on the reference that is used [Wallentin, 2011]. If an expensive biocide free hull paint system is used then the ship's hull may be blasted down to steel. Normally an older, 10-15 year old, vessel would be selected from a fleet for such surface preparation, so the full blast will bring the hull from the worst condition to the best condition. The improvement in the fuel consumption from this surface preparation can be between 25% and 40% depending on the prior condition [Wallentin, 2011]. This means that in some cases high fuel savings can be guaranteed by manufacturers; this illustrates that a standard in hull performance measurement is required that is transparent [Wallentin, 2011].

As well as applying a coating certain techniques can also be used to reduce skin friction resistance, possibly by manipulation of the boundary layer. In one instance, Royal Navy trials on a surface ship showed the injection of a polymer, polyox, at very low concentrations gave reductions in skin friction drag of up to 20% for very short periods of high speed running [Rawson and Tupper, 2001]. However, a more practical and promising reduction in resistance can be achieved by injecting air between the ship's hull and the water.

### 3.2.4 Air injection

There are three main ways to use air in order to reduce resistance [Foeth, 2008]:

- Injecting air bubbles in the boundary layer.
- Use of air films along the bottom plating.
- Air cavities in the ship's bottom.

The method in which air lubrication reduces resistance can be complex and may also impact on the propulsion coefficient and the wave-making component of resistance. Equation 3.1 is adapted from a paper from Maritime Research Institute Netherlands (MARIN) [Foeth, 2008] and assumes that air lubrication only affects skin-friction resistance:

$$C_T = (k + k_2) \times C_F + C_R + C_A \tag{3.1}$$

In Equation 3.1:

$C_T$ is the total resistance coefficient.

$C_F$ is the frictional resistance coefficient, this can be given by the ITTC 1957 ship-model correlation line.

$C_R$ is the residuary resistance coefficient.

$C_A$ is a correction factor, to account for differences between model and ship.

$k$ is a factor to account for 3D effects, where $(k + 1)$ is the form factor.

$k_2$ is the change in frictional resistance due to air lubrication, this could also be modelled as a change in wetted surface area.

Air bubble lubrication has the benefit that only small changes to the hull are required; only very small holes in the hull are required compared to an air cavity air lubrication system. Full-scale air bubble injection trials were conducted at MARIN [Foeth, 2008] [Foeth et al., 2009]. Although previous small-scale laboratory tests have shown that air bubble injection (without an air cavity) can be used to reduce resistance, the $CO_2$ emission reductions found from small-scale results could not be repeated at larger scales, where no appreciable effect on resistance, propulsion and manoeuvring characteristics was found, the mechanism by which micro bubbles reduce resistance remains unclear and the air-water interface is hard to model [Foeth et al., 2009].

By using an air cavity air lubrication system that guides the air flow, in this case this consisted of a chamber split into 3 longitudinal sections that tapers towards the end, the company DK group claimed fuel-savings of up to 15% and that the technology could be retrofitted in 14 days in dry dock [IMarEST, 2010b].

All air injection systems require constant pumping power so if a ship travels too slowly this becomes a significant part of the propulsive power [Foeth et al., 2009]. Additionally, it may be necessary to consider the leakage of air; the leakage of air into the propeller may have an impact on the propulsion efficiency as well as the performance of the air injection system. Air lubrication appears to provide the most predictable reduction in $CO_2$ emissions when using an air cavity, especially when retrofitting to existing ships. In some instances, air lubrication may represent significant savings, but these savings are hard to predict and quantify. It is also more suited to ships where frictional resistance is a high proportion of total resistance and to flat-bottomed ships, less flat-bottomed ships do not fair so well because of leakage [Foeth, 2008].

## 3.3 Reducing the Auxiliary Power Requirement

Reducing auxiliary power is likely to have a small $CO_2$ emission reduction potential on the overall ship compared to reducing the main engine power. An exception to this is passenger ships that can have a very large hotel load.

Auxiliary power needs to provide power to:

- Navigation, Manoeuvring and Communication (e.g. control system, radar, etc.)
- Hotel (e.g. HVAC, lighting, appliances, laundry, waste treatment, fresh water)
- Cargo Support Systems - to support loading and unloading and heating and cooling of cargo
- Ship Support Systems - (e.g. sea water and power distribution, fuel and engine support)

For cargo ships an appreciable reduction in $CO_2$ emissions from auxiliary power is more likely to be from a reduction in energy use associated with the heating and cooling of cargo. Container ships in particular have a potentially large load due to reefer containers. To put this into context, from comparison of some ships given in Clarksons [Clarksons, 2010] and RINA's Significant Ships [RINA, 2007] the installed auxiliary power in a container ship can provide, roughly, around 80% to 88% of the propulsion requirement of an equivalent sized bulk carrier. Although container ships have a higher design speed than a bulk carrier, with more power being used for propulsion rather than to chill or refrigerate containers. Even so, for a 25 knot container ship a 2.7% reduction was estimated by converting just the auxiliary power fuel from Heavy Fuel Oil (HFO) to Liquified Natural Gas (LNG) [Calleya et al., 2011a]. In order to model the heating and cooling energy use accurately the energy required for the cargo support systems should be modelled separately from the hotel and other ship loads.

## 3.4 Managing Energy more Efficiently and using Alternative Fuels to Oil-based Fuels

Section 3.2 and 3.3 have discussed the potential reduction in $CO_2$ emissions by reducing the power requirement to propel and manoeuvre the vessel and for auxiliary functions. This section considers different energy sources and how to manage the flow of energy. Considering the ship as a system at a high level the energy flows within a ship can be represented as shown as in Figure 3.1.

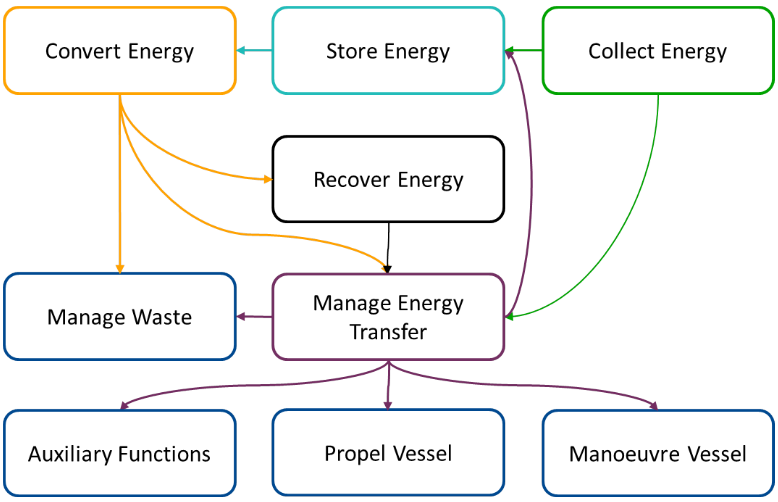



Figure 3.1: Diagram showing energy flows in a generic vessel used in the ETI HDVE project (the ETI HDVE project is explained in Appendix B). *This diagram is not the authors own work and was created by R. Pawling.*

When the whole energy system of the ship is assessed, as in Figure 3.1, it becomes clear that energy conversion and storage of energy are difficult. There are losses whenever energy is converted from one form to another. This means that when considering what power generation equipment or marine systems to use it is necessary to consider the type of energy that is required or available, such as mechanical or electrical. For example, if a reciprocating engine is used with a propeller energy conversion losses can be reduced by having the propeller mechanically connected to the engine.

When considering energy sources and energy distribution systems there are a few considerations; the energy sources, the mechanical and electrical power generation equipment (to convert stored energy to useful energy) and the layout of the marine systems.

### 3.4.1 Energy sources

As with the rest of this Chapter, this is intended to give a suitable overview of each of the options because with different design and operational constraints some solutions may be more suitable than others. Although energy sources and their implementation could be an area for much more analysis, the focus is on the short-term future and sources of energy; with a very high TRL, as defined in Section 1.2. A wide range of energy options have been mentioned briefly to ensure that the selected options that get chosen for further analysis have been selected with knowledge of the alternatives.

There are a few ways that energy could be stored:

- In chemical bonds.
- In the atoms themselves (radioactive isotopes used for nuclear energy).
- As mechanical (kinetic or potential) energy.
- As gravitational potential energy.
- As electricity.
- As heat.

Chemical bonds are how energy is stored in fuels, such as hydrocarbons, and batteries, using ionic chemical bonds. Mechanical energy storage could be a flywheel or compressed gas. Electrical energy is the storage of electrical charge, a capacitor is an example of this, although electrical energy is not normally stored directly. Different types of energy storage are sometimes used in conjunction with each other. For example, compressed air energy storage is used in conjunction with Diesels or gas turbines [RAEng, 2013]. Heat may be an impractical way of storing energy as the heat requirement for a ship is small compared to the electrical or propulsive requirement so heat has to be converted to another form of energy to be useful and any conversion has losses associated with it, though waste heat can normally be used to provide the small HVAC and fuel heating requirements.

Energy storage methods have been extensively discussed as part of future transport and energy systems [European Commission, 2011] [U.S. Department of Energy, 2013] [RAEng, 2013]. Focussing on ship application, the current or possible energy storage mechanisms are:

- Oil-based fuels (including Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) and Intermediate Fuel Oils (IFOs)).
- Methane (stored as Liquid Natural Gas (LNG) or Compressed Natural Gas (CNG)).
- Liquid Petroleum Gas (LPG) (can be a mixture of propane and butane).
- Ammonia.
- Methanol.
- Ethanol.
- Hydrogen (stored as compressed gas or possibly as a metal hydride).
- Electricity.
- Compressed Air or Liquid Nitrogen.
- Nuclear.

#### 3.4.1.1 Oil-based fuels (including Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) and Intermediate Fuel Oils (IFOs))

Oil-based fuels are widely used and have a well-established fuel infrastructure. Oil-based fuels are a cheap energy source that have a high energy density and are easy to store as a liquid, especially when compared to alternative fuels. The continued use of oil-based fuel in the short-term is very likely alongside efficiency improvements to the existing associated mechanical and electrical power generation equipment and possibly supplemented by other energy sources.

#### 3.4.1.2 Methane (stored as Liquid Natural Gas (LNG) or Compressed Natural Gas (CNG))

Though not as energy dense as oil-based fuels, natural gas (or methane) is considered as an alternative to oil-based fuels due to having both a favourable energy density and price when compared to other alternatives to oil-based fuels, such as hydrogen.

Using natural gas as a fuel can also reduce $CO_2$ emissions by 25% compared to oil-based fuels

[RINA, 2010c] due to having a lower carbon to hydrogen ratio in it's chemical composition. Though one of the incentive for increasing use of natural gas is due to ECAs, as using natural gas significantly reduces $NO_x$, $SO_x$ and PM emissions when compared to oil [RINA, 2010c], with the first LNG ferry being ordered in 2010 [Fast Ferry International, 2010].

Since 1964 a number of LNG carriers have been in operation using Boil Off Gas (BOG) as fuel for the propulsion machinery [Einang and Haavik, 2000]. The established natural gas and LNG carrier market initially advanced the current classification society rules for the storage of both liquid and gaseous fuels.

Hydraulic fracturing has increased the reserves and changed the geographical distribution of natural gas. The recent combination of horizontal drilling and hydraulic fracturing can extract huge quantities of natural gas from impermeable shale formations, which were previously thought to be either impossible or uneconomic to produce [Wang et al., 2014]. This means that in the future shale gas will be the main driver for US natural gas independence [Wang et al., 2014].

Section 4.2 contains a detailed ship design study of natural gas that was carried out.

#### 3.4.1.3 Liquid Petroleum Gas (LPG) (can be a mixture of propane and butane)

Liquid Petroleum Gas (LPG) is not as clean as natural gas but an LPG supply network is easier because it is less costly and it is perceived as being safer because it has had more use and is more familiar. LPG is a by-product of LNG which is set to see an increase in demand, so LPG production is also likely to increase too [IMarEST, 2010c].

#### 3.4.1.4 Ammonia

Ammonia is a widely used chemical and a small network for the distribution of ammonia does exist although it this would need to be much larger if ammonia were to be used as a fuel. Ammonia is currently normally made from natural gas [RAEng, 2013], although it is possible to make ammonia from water, this means it will likely be more expensive than natural gas and produce more $CO_2$ emissions in it's manufacture.

#### 3.4.1.5 Methanol

Methanol is not a new idea as a fuel and a report by Lloyds Register highlights it's use as a fuel for ships when compared to natural gas [Lloyds Register, 2013]. By producing methanol, the existing oil product transportation, storage and distribution infrastructure can be used and the need for capital investment in new infrastructure is considerably reduced [Lloyds Register, 2013]. As with the majority of energy sources discussed here the amount of $CO_2$ emitted and the cost of the fuel also depends on how the fuel is made, Methanol can be made from natural gas [Lloyds Register, 2013] and is also toxic.

#### 3.4.1.6 Ethanol

Ethanol is normally produced as a biofuel and can be referred to as bioethanol. There are a range of different biofuels available including bioethanol so the issues associated with biofuels and their use (including bioethanol) are discussed in more detail in a separate Sub-subsection, Sub-subsection 3.6.1.1. Bioethanol can be produced from renewable sources of sugar or starch [RAEng, 2013]. Brazil established ethanol as an alternative fuel to petroleum in 1975 to support it's sugar industry in the wake of collapsing sugar prices and to reduce it's energy dependence on petroleum and other countries [Hira and Guilherme de Oliveira, 2009]. This was initially stimulated by govenment policies and later was revitalised by flexible fuel vehicles [Hira and Guilherme de Oliveira, 2009], that can run on different blends of ethanol and petroleum.

#### 3.4.1.7 Hydrogen

Though hydrogen is an effective way to store renewable energy, there are some fuel infrastructure and storage barriers for the use of hydrogen as a fuel for ships. Hydrogen requires a new fuel infrastructure to be developed for it's manufacture and distribution as a fuel and is currently made from natural gas [RAEng, 2013]. As discussed in Section 2.2, in future if aviation uses hydrogen as a fuel this may effect the hydrogen infrastructure that could be available for shipping. Metal hydrides and research into carbon nanofibres are alternative ways to store hydrogen, unfortunately metal hydrides have a high density [Greig, 2003].

For production of hydrogen water is not normally an acceptable source of hydrogen because more energy is needed, using electrolysis, to extract hydrogen from water than can be removed from the hydrogen generated; Diesel fuel and methanol are both effective hydrogen vectors [Greig, 2003].

#### 3.4.1.8 Nuclear

The operational $CO_2$ emissions from nuclear power would be near zero (Diesel generators, or similar, will be needed to start up reactors, as a backup and may be needed in some ports). Nuclear power was introduced in a few merchant ships in the 1960s, but proved too expensive to operate [Carlton et al., 2010]. Although the through-life costs of nuclear power are comparable to a conventional ship, the costs are more biased to the initial purchase cost [Carlton et al., 2010].

The safety culture required for a nuclear ship has to pervade the whole operating, owning and regulating structure. The companies supporting both the civil and military nuclear power sectors would be key to the development of the required safety culture and training regimes. Being allowed into certain ports may be an issue [Carlton et al., 2010]. Given the differences between the seagoing merchant and naval engineering training, the present merchant training would require significant modification [Carlton et al., 2010]. There are also additional costs associated with fuel and decomissioning [Carlton et al., 2010].

One focus has been on ice breakers [Carlton et al., 2010]. Ice breakers require much more energy than a conventional ship to get through ice and they operate in remote locations so they are more suited to utilising nuclear power as a propulsion plant.

Though nuclear power has had a low accident rate [George, 2011] and terrorist threats are more a perceived risk [Carlton et al., 2010] that has not stopped people being anxious [George, 2011]. It has been suggested that this is because it is invisible and not understood by the general public [George, 2011]. Public perception can be a barrier to the adoption of CRMs, particularly nuclear power, this was discussed in Subsection 2.7.1.

It may possible that in the longer term extreme $CO_2$ emissions targets may advocate nuclear power as a zero operational $CO_2$ emission source of energy for ships.

### 3.4.2 Renewable energy sources

The amount of energy available from renewable energy sources depend on the environmental conditions. This means that renewable energy sources are likely to be supplemented by non-renewable energy sources, such as oil-based fuels and methane:

- Wind.
- Solar.
- Wave.

These energy sources are different to the energy sources listed in Subsection 3.4.1 because energy is not stored in these forms but is externally available from the environment.

#### 3.4.2.1 Wind

Wind energy can be used to generate electricity, via a wind turbine, or to save fuel and/or increase speed, via sails or magnus-effect devices. Sail assisted propulsion (sails operating in conjunction with a Diesel engine) has been proposed to allow the ship to operate effectively in all conditions. Full scale trials on the sail assisted propulsion ship Mini Lace, a 3 000 tonne deadweight general purpose cargo ship fitted with a soft sail cat rig, over 18 months found a 24% reduction in fuel consumption with a 4.4 year investment period [Bergeson and Greenwald, 1985]. An alternative to sails is kites. Kites do not suffer from the stability problems of high masts [Hochkirch and Volker, 2010], but do require deployment and recovery mechanisms.

Section 4.3 contains a detailed ship design study of wind energy that was carried out.

#### 3.4.2.2 Solar

Solar energy can be generated from the sun by heating water or by, more directly, converting light to electricity using a solar cell. For cases when hot water is required, heating water directly is simpler and may be more cost-effective than using solar cells. Photovoltaic solar cells (PVs) have a low efficiency and are limited by the amount of available deck area on a ship, you would be unlikely to get more than around 400 W/m$^2$. An efficiency of PVs of up to 30% may be expected by 2020 [Det Norske Veritas, 2011b]. This may make PVs not very cost-effective, although specific markets, in terms of ship types and voyage routes, may benefit from solar energy more than others. For example, NYK uses solar cells on RORO (Roll-On/Roll-Off) car carriers [NYK Group, 2012], these have a large deck area and carry a specialist cargo that means that the time in port may be longer compared to some other ship types. Car carriers may be more affected by both port emission controls and ECAs.

#### 3.4.2.3 Wave

Wave Power extraction systems for ships can be internal (gyro-based) or external (wavefoils, stern flaps or relative movement between multiple hulls). High technical complexity and limited energy efficiency make such systems not very promising [Buhaug et al., 2009]. There has been indication of some power generated via electromagnetic induction using a llinear generator on a small yacht [Guizzi et al., 2013]. There may be further energy extrapolations by designing a ship's hull, with less stiffness in pitch and roll, to use the benefits of extracting energy from ship motions.

#### 3.4.2.4 Electricity

Though the size of batteries is not practical for full battery propulsion [RAEng, 2013], short route ferries are a notable exception to this. For larger ships batteries and capacitors can play a role in supplementing other energy sources.

#### 3.4.2.5 Compressed air and liquid nitrogen

Compressed air and liquid nitrogen is potentially a way of storing and using energy that creates very low operational $CO_2$ emissions. The energy density of compressed air and liquid nitrogen is low (with liquid nitrogen requiring cryogenic systems) [RAEng, 2013]. Additionally, it may be necessary to heat the gas when it expands to stop systems (possibly the engine) from freezing, especially without a large heat sink.

### 3.4.3 Mechanical and electrical power generation equipment

Though it depends how energy is stored, energy is normally converted to mechanical or electrical energy to be used by the equipment on-board a vessel.

There are some different engine types which could be used as marine power plants, but need some investment to be developed. Such as the stirling engine or opposed cylinder arrangement engine, with two pistons in each cylinder [IMarEST, 2011b], which has been used in the past. It is not clear whether these alternative engine arrangements can be cost-effective or offer any benefit at the size required for the propulsion for large ships. One proposed concept uses a form of propulsion that utilises gyroscopes powered by a Diesel generator to cause pulses of thrust [IMarEST, 2010a], this has a low TRL and may not even be viable.

#### 3.4.3.1 Internal combustion engines

Diesel technology is well understood and reliable with infrastructure, training and spare parts already in place [RAEng, 2013].

Two-stroke and four-stroke engines can be designed to run on many fuels, including alcohols and hydrogen as well as hydrocarbon based fuels, such as natural gas. It is currently possible to order engines that run on natural gas and to convert existing engines to run on natural gas [Einang, 2011]. This use of natural gas as a fuel is discussed in Section 4.2.

In future, ultra-long stroke engines may result in a lower speed and larger propellers giving reductions in fuel consumption of around 4.6% (the majority of this fuel saving comes from the propeller operating more efficiently at lower speeds [IMarEST, 2011d]).

#### 3.4.3.2 Gas turbines

Gas turbines are a well established and understood technology and were designed to burn distillate fuels to meet emission regulations and can readily burn lighter distillates and gas fuels. Gas turbines can be designed to run on many fuels, including alcohols and hydrogen as well as hydrocarbon based fuels, such as natural gas. Thermal efficiencies are lower than for Diesel engines of similar power [RAEng, 2013] this means that they have a higher specific fuel consumption. Gas turbines were developed for aviation which has many requirements in common with the marine needs; robustness, size and mass are as important as efficiency [Greig, 2003], although the power to mass ratio is more critical for aviation. This means that gas turbines have a smaller mass but require gearboxes due to operating at a much higher rotational speeds compared to Diesel engines. Further developments involving complex cycles, such as the Rolls Royce WR-21, are still ongoing, offering improved specific fuel consumption at the expense of increased machinery weight and complexity.

#### 3.4.3.3 Steam systems

Steam systems (including steam turbines, boilers, feedpump, condenser, etc.) require external heat. Heat is sometimes provided by using a fuel to heat a boiler or using other sources of heat. Steam propulsion systems have been used on LNG carriers since the 1960's and are well proven and reliable. However, the maximum efficiency of the steam propulsion system is approximately 30% at full load and this gets lower as the turbine load goes down [Yeo et al., 2007]. This is much less than the efficiency of a typical two-stroke or four-stroke internal combustion engine. Although not widely used as a primary means of propulsion for modern ships, with the exception from LNG carriers, steam systems are still employed as part of a waste heat recovery system and in nuclear power plants.

#### 3.4.3.4 Fuel cells

High temperature fuel cells have the potential to exceed the efficiencies of Diesels and gas turbines. If the waste heat is utilised then much higher efficiencies are possible although this is also true of gas turbines and Diesels [Greig, 2003]. However fuel cells have the following barriers to being applied [Chung Tse et al., 2011]:

- Costs are high (inland river boats, where emissions controls may be more severe [RINA, 2010c], large luxury yachts and submarines can be considered as entry markets).
- High temperature fuel cells have a long start-up and stopping time.
- Limited load following capability, this suits auxiliary power applications and can be compensated by an energy storage system or gas turbine.
- There is a need to control the humidity of incoming air.

Start-up times are related to operating temperatures. Proton Exchange Membrane Fuel Cells (PEMFCs) have already demonstrated start up times of less than 2 minutes although they have a maximum size of around 50 to 100kW. High temperature fuel cells, Molton Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs) are more efficient [Greig, 2003]. Although high temperature fuel cells have long start up times of about 10 hours and poor efficiency at low power when they may require external heating. The long time is necessary to prevent any damage from the differential expansion of the many components. Reducing start-up time has not been a significant design driver (not required for land-based plants). For merchant ships which have a more predictable operating profile and less requirements for peak power demands long start up times would be less of a constraint [Greig, 2003].

In general, the higher the fuel cell operating temperature the higher the theoretical efficiency and less fuel reforming (needed if hydrogen is not used) is required, while at higher temperatures there is also a greater opportunity of useful co-generation. Power output is proportional to the cell surface area and the area of any one of the cells is limited. The result is that a 1MW fuel cell power unit would consist of a number of stacks rather then one big stack. This gives the designer much more flexibiility in the layout of the power plant [Greig, 2003]. Fuel cells also produce DC power directly so may have additional benefits if used as part of a potentially more efficient, compared to AC, DC electrical power system.

A solid oxide fuel cell can be combined with a gas turbine to help it's part load efficiency. A Solid Oxide Fuel Cell combined with a Gas Turbine (SOFC-GT) can also be run on a number of different fuels such as hydrogen (low power density), liquid hydrocarbons, Diesel (preferred at the moment as uses existing existing infrastructure), LPG and LNG (are long-term options) [Chung Tse et al., 2011].

At the moment using fuel cells for auxiliary power in a combined heating, cooling and power system seems the most probable. However current applications are too small scale for large commercial ships (around 250kW) [Chung Tse et al., 2011]. The marine industry is unlikely to support major research efforts in fuel cells and high power fuel cells being developed for the land-based power generation industry have a different set of priorities that do not match so well with marine requirements. The exception to this being air independent propulsion for submarines and autonomous underwater vehicles [Greig, 2003].

### 3.4.4 Layout of marine systems

As mentioned in Subsection 3.4.3, there are a few ways in which energy sources can be used on their own or in combination in order to improve the overall efficiency of a ship. Any changes to the ship also should not cause a adverse effect on performance, in some markets if a ship has unpredictable performance and cannot maintain a schedule then it may be less profitable.

Renewable energy such as photo-voltaic solar panels and wind power are most likely to be used to supplement more conventional forms of propulsion, rather than being used as a primary method of propulsion [Hochkirch and Volker, 2010]. Sail assisted propulsion is more economically advantageous when used in conjunction with conventional screw propulsion, pure sailing ships are uneconomical [Bergeson and Greenwald, 1985].

#### 3.4.4.1 Shaft generators and motors

Shaft generators and motors allow for the integration of main power and auxiliary power systems. Shaft generators and motors are fairly common on large vessels and may become much more common in future. Some vessels can use shaft generators and motors as a Power Take-In (PTI) as well as a more common power take-off (PTO), this can be in a single combined shaft generator and motor. A PTO normally uses mechanical power from the main engine to generate electricty in order to reduce fuel consumption, larger main engines normally have a lower overall specific fuel consumption compared to the auxiliary power generators.

A PTI is a motor that converts electrical power from a vessels auxiliary power to mechanical power that is used to provide additional power to the shaft. This can be used to reduce the required sea margins on the main engine, which are expensive and only needed on rare occasions [Hochkirch and Volker, 2010].

#### 3.4.4.2 Waste heat recovery

Waste heat recovery is used on some large vessels with more installed power, particularly container ships, however the investment period can be over 4 years for a large container ship [MAN, 2012b]. Faster ships, such as container ships will have a bigger potential fuel saving from waste heat recovery. The waste heat recovery system on a bulk carrer may not be economically viable at all due to the relatively large investment cost [Eide et al., 2009]. The energy utilisation from waste heat recovery is calculated to be in the range of about 3.5% of the shaft power [Buhaug et al., 2009]. This 3.5% is on the main engine only. In order to approximately estimate the $CO_2$ emission reduction on the overall ship, if it is assumed that the ratio of the main engine fuel use to the total fuel use (main engine fuel use and auxiliary engine fuel use) is 80%, then the $CO_2$ emission reduction, in this case synonymous with fuel consumption, is approximately 3%.

For current waste heat recovery systems there has to be a large enough flow of heat to drive the power turbine. The power turbine starts power production at around 40% to 50% of the main engine MCR [MAN, 2012b]. This means that waste heat recovery can only be used at high ship speeds. There may be some improvements in future as marine waste heat recovery plants are developed further, possibly by using multiple smaller turbines rather than fewer larger turbines and by using organic Rankine cycles.

#### 3.4.4.3 Power distribution improvements

Energy and power management can be quite inportant to improve efficiency, especially when you consider that a ship should be designed to work over a typical operating profile, and to take full advantage of CRMs such as CRTs or operational CRMs, such as “virtual arrival”.

A Diesel-electric propulsion and power distribution system can be used although this is normally less efficient than a hybrid arrangement [Buckingham, 2013] due to conversion losses, especially when maintaining a operating profile with a narrow band of speeds as with cargo carrying ships. By hybrid it is meant that a mechanical propulsion system is used with a PTO and PTI to distribute distribute power to and from, respectively, the electrical system (or auxiliary power). More specialist ships with more variable operating profiles may benefit from Diesel-electric propulsion. A DC electrical distribution can also be used for higher efficiencies if a system is probably setup to take advantage of the benefits, a lot of AC consumers will likely be used too. ABB has a DC system for Offshore Supply Vessels (OSVs) [Hansen et al., 2012], that may offer fuel consumption savings over an operating profile.

There are also other small ways to better manage the energy onboard such as implementing variable speed pumps and fans where possible.

Operational carbon dioxide reducing measures, such as cold ironing, can also have an effect on how on-board power is used.

#### 3.4.4.4 Cold ironing

Cold ironing is the practice of using electricity provided by the port. Cold ironing can potentially reduce $CO_2$ emissions from ships, but the overall $CO_2$ emission reduction also depends on the source of energy used on the ship and the source of the energy used in port. Cold ironing has to be provided by the port and is outside the scope of this work, as defined in Section 1.2. Where cold ironing is to be included there is also the decision of how to account for the embedded carbon in the electrical supply and what carbon factor to use (this could be defined as the amount of tonnes of $CO_2$ emitted per kW). In this case, the carbon factor is zero because the $CO_2$ emissions from a port are not associated wth the ship.

## 3.5 Capture and Storing versus Recycling $CO_2$ (and other GHGs)

Currently over the next 10 to 20 years capturing and storing $CO_2$ is an additional cost that does not provide the shipowner or charterer with a financial or any other incentive, unless a legislative or taxation incentive is introduced in future. Some of the other CRTs mentioned in Sections 3.2, 3.3 and 3.4 may be profitable in their application, normally through reducing fuel cost. Reducing costs using Carbon Capture and Storage (CCS) is only expected for the injection of $CO_2$ in order to recover oil [Pires et al., 2011].

Carbon or carbon-dioxide can be removed in post-combustion capture systems, pre-combustion capture systems or during combustion by recycling the fuel [Pires et al., 2011]. On-board ships it may be possible to capture $CO_2$ from flue gases using microalgae [Pires et al., 2012]. However in shipping because this does not provide an incentive there would have to be regulation to limit ship-board $CO_2$ emissions, possibly some form of carbon taxation. $CO_2$ emission reduction incentives are discussed in Section 2.4. Intensive research and demonstration is also required to reduce the costs associated with all parts of CCS [Pires et al., 2011].

When considering CCS the whole lifecycle of a fuel and fuel infrastructure should be considered. Selecting alternative fuels to oil-based fuels with a lower carbon content or possibly manufacturing fuels from $CO_2$ may be important.

The cost of CCS can be used to set a price ceiling of emitting $CO_2$ (or a $CO_2$ taxation). By finding the point at which the price of emitting $CO_2$ is more than the cost of a CCS system that stops the equivalent amount of $CO_2$ being emitted. With a $CO_2$ emission taxation at this price point additional increases in the taxation level would have little effect, as the CCS system may have already been adopted.

Considering a CRM that is dependent on new tax and legislation is beyond the scope of this work, as defined in Section 1.2.

## 3.6 Selection of Carbon Dioxide Reducing Technologies (CRTs) and Energy Sources

This Section will initially compare the different sources and ways of using energy discussed in Section 3.4 then discuss the remaining CRTs mentioned in Sections 3.2, 3.3 and 3.4

### 3.6.1 Energy source selection

Table 3.1 shows a comparison of the different fuels that were examined in this study. By comparing between different energy sources, especially comparing to oil because that is what is most widely used at the moment, a simple comparison was made by estimating both the potential for $CO_2$ emission reduction and cost reduction. One factor that was consided in this comparison is that currently some fuels (or energy sources) are made from other fuels, natural gas is used to make both ammonia and hydrogen [RAEng, 2013]. A fuel made from another fuel is likely to be both more expensive and have increased $CO_2$ emissions from its manufacture.

| Energy source (or fuel) | Potential for $CO_2$ emissions reduction | Potentital for cost reduction | Main Justification (from literature review in Subsection 3.4.1) |
|---|---|---|---|
| Oil-based fuels | None | High | Well-established infrastructure and equipment. |
| Methane (LNG or CNG) | High | Low | Fuel price and infrastructure costs are hard to estimate. |
| Liquid Petroleum Gas (LPG) | Low | High | This is a byproduct of producing natural gas. |
| Ammonia | High | None | Ammonia does not contain any carbon and is currently produced in large quantities from natural gas. |
| Methanol | High | None | Fuel infrastructure is required. |
| Ethanol | High | None | Fuel infrastructure is required. |
| Hydrogen | High | None | Fuel infrastructure is required. |
| Electricity | Low | Low | Electrical energy is not normally stored directly. |
| Compressed air or liquid nitrogen | High | None | Fuel infrastructure is required. |
| Nuclear | High | High | High potential but some difficult barriers to overcome. |
| Wind | High | High | Initial costs may be high and intermittent. |
| Solar | High | Low | Initial costs may be high and intermittent. |
| Wave | Low | Low | Initial costs may be high and intermittent (may not always be feasible). |

Table 3.1: Comparison of different energy sources for use in the short-term future. The potential for reducing $CO_2$ emissions and costs is shown as Low, High or None.

We are concerned mainly with the operational $CO_2$ emissions of the ship, so the fuel infrastructure and the $CO_2$ emissions embedded in the manufacture of different fuels is outside the shipping system boundaries defined in Section 1.2. The fuel infrastructure refers to anything associated with the fuel production that requires significant development and investment, this could include bunkering facilities in ports, regulation or, in some cases, such as with nuclear ships, the ability to even enter a port. In some cases a dedicated refuelling system may be needed. For example, the first LNG ferry in Norway was refuelled from a truck [Einang and Haavik, 2000]. The fuel infrastructure also relates to the potential for cost reduction that is shown in Table 3.1.

Nuclear power looks promising in terms of no $CO_2$ emissions and potentially lower fuels costs over the ships lifetime [RAEng, 2013]. However, nuclear power has infrastructure barriers and also has higher initial costs, which means the ship has a longer investment period.

When considering infrastructure as a barrier, what fuels potentially provide a good chance of reduction in $CO_2$ emissions and a potential reduction in cost (represented by a Low, High or None in Table 3.1) then there are four likely energy options for ships in the short-term:

- Oil-based fuels.
- Methane (LNG or CNG).
- Wind.
- Solar.

In order to understand the full impact of switching to alternative fuels, consideration of the through-life $CO_2$ emissions is important. Especially considering that marine transportation routinely uses residual fuel, both a waste product of petroleum refining and a blended product itself [Winebrake et al., 2006]. The entire lifecycle $CO_2$ emissions of the fuel is out of the scope of this study, see Section 1.2.

#### 3.6.1.1 Use of biofuels

Biofuels have not been discussed as a fuel option because whether or not a fuel is a biofuel depends on how the fuel is produced, fuels can be derived from fossil fuels, such as oil or gas, or non-fossil fuel (possibly renewable) sources, and this generally does not effect how the fuel is used on the ship.

In use the shipboard $CO_2$ emissions of a fuel derived from biofuel or from a fossil fuel will be similar, biofuels should be described carefully because the reduction in $CO_2$ emissions from biofuels comes from the manufacturing process. For most sources of biofuel, such as algae [Det Norske Veritas, 2011b], vegetable oil, sugar or starch [RAEng, 2013], the $CO_2$ emission reduction comes from the $CO_2$ required to support plant growth. As biofuels are not derived from fossil fuels they may also have additional emission benefits because they do not contain impurities, such as sulphur.

Biofuels, particularly as replacements for oil-based fuels, are promising because they allow the existing shipboard equipment to be used, the changes required to engines can be minimal. However biofuels are expensive due to the fuel infrastructure required to produce large quantities of biofuel [Det Norske Veritas, 2011b]. Some sources of biofuel also compete with food production [Det Norske Veritas, 2011b]. Additionally, as mentioned in Subsection 2.2.4, the aviation industry will be more prepared to pay a premium for a liquid high energy density fuel.

## 3.7 Summary and Conclusions

From the literature the potential $CO_2$ emission reductions due to CRTs are approximate. Without more detailed analysis of CRMs the reasons for rejecting CRMs for use in the short-term are:

- Outside the shipping system scope (defined in Section 1.2).
- Better alternative CRT - having a higher TRL, requiring less infrastructure or development cost.

In most cases CRTs have been rejected because the Through-Life Cost (TLC) and Unit Purchase Cost (UPC) is very likely to be higher than an alternative CRT with at least the same reduction in $CO_2$ emissions. Where this has been unclear the CRT has not been rejected and will be investigated further. For example, gas turbines and steam turbines are likely to be more expensive than a Diesel engine and have a lower potential reduction in $CO_2$ emissions. In specific ship designs, such as slender hulled catamarans [Fast Ferry International, 2010] where space in the machinery spaces is limited, gas turbines may be advantageous. However, for large commercial ships weight and space for equipment and machinery is not so limited.

Operational CRMs were not completely rejected as out of the scope of this work because they effect the ship design indirectly (compared to a CRT) and can effect how the ship and CRTs are used. Two operational CRMs, cleaning and maintenance and operating speed profile, were identified in Subsection 2.6.6, as operational assumptions that can vary and should be considered for different ship and CRT combinations. These are shown in Table 3.2. Both weather routing and heading control and trim optimisation were rejected as being difficult to model accurately with the available data and out of the scope of this work, defined in Section 1.2.

Oil-based biofuels are outside the scope of work, defined in Section 1.2, because they do not require any changes to the ship and the $CO_2$ emission reduction comes from the manufacturing process. If required biofuels could be assessed in more detail, but ships require minimum modifications to incorporate them.

In Table 3.2 electricity is not a primary energy source but a baseline assumption because it is a well-established way of transmitting energy on a ship. It is included to cover all the options. Small batteries are also used in exisiting ships for start-up of engines and sometimes for load smoothing. Storing a very large amount of energy in electrical batteries for propulsion is not financially viable. Using batteries for large consumers, such as a bow thruster, can be considered. However, this is difficult because you may need to provide a back-up engine for the case where the battery is not fully charged. It is unlikely a ship owner would pay for two sets of equipment that can carry out the same task, unless there is financial incentive or a regulatory requirement.

Generally the CRTs that will be selected to be used on ships in the short-term future are:

- Relatively easy to implement (likely to have a high TRL).
- Have a high potential for reducing $CO_2$ emissions.
- Can reduce operational costs.

In order to better develop a model to examine different ship and CRT combinations it is also necessary to investigate CRTs that have large and different impacts on the ship. Two CRTs that satisfy the above criteria, giving a large potential reduction in $CO_2$ emissions and having large and differing impacts on the ship are wind power and LNG so these will be investigated in more detail in Chapter 4.

| How CRM is modelled | Carbon Dioxide Reducing Measure (CRM) | Literature Review $CO_2$ reduction (if mentioned) |
|---|---|---|
| Rejected - Outside the shipping system scope (defined in Section 1.2) | Ballast management and logistics | |
| | Weather routing and heading control | 1% [Sustainable Shipping, 2010] |
| | Trim optimisation | 5% [Hochkirch and Volker, 2010] |
| | Cold ironing | |
| | Shaft generators | |
| | Oil-based biofuel | |
| Rejected - Better Alternative CRT | Gas turbines | |
| | Steam systems | |
| | Power distribution improvements | |
| Simple CRT Model | Improve propulsion coefficient | 4% [Hochkirch and Volker, 2010] |
| | Hull coatings | 4% to 6% [IMarEST, 2011a] |
| Simple and Complex CRT Model | Wind | 24% [Bergeson and Greenwald, 1985] |
| Complex CRT Model | Air injection | 15% [IMarEST, 2010b] |
| | Solar | |
| | Fuel cells for auxiliary power | |
| | Waste heat recovery | 3% [Buhaug et al., 2009] |
| Primary Energy Source Options | Oil-based fuels | |
| | Methane (LNG or CNG) | 25% [RINA, 2010c] |
| Operating Assumptions | Cleaning and maintenance | 5% [Buhaug et al., 2009] |
| | Operating speed profile | 20% to 30% [Corbett et al., 2009] |
| Baseline Assumptions | Internal combustion engines | |
| | Electricity | |

Table 3.2: Carbon Dioxide Reducing Measures (CRMs) that are technically feasible from the literature review and how they could be integrated into a ship model.

## Chapter 4

# Ship Design and Implementation of Carbon Dioxide Reducing Technologies (CRTs)

## 4.1 Whole Ship Model (WSM)

The Whole Ship Models (WSMs) are full three-dimensional early stage ship design models that have the purpose of accurately representing specific commercial ship types. The WSMs are partially parametric (they are not fully parametric because it is necesary to avoid losing design detail). The WSMs should respond accurately to changes to the ship due to Carbon Dioxide Reducing Technologies (CRTs). The WSMs were created in the ship design software Paramarine [QinetiQ GRC, 2013]. Figure 4.1 shows the level of detail in the WSMs.

The mathematically modelled approximations stem mainly from empirical analysis of existing ships or from direct calculation and modelling. Sufficient safety, efficiency and utilisation factors are also needed to model real world results using approximate calculations.

### 4.1.1 Ship survey

There is a huge diversity in the world's fleet and the model is limited to just four ship types: container ships, bulk carriers, oil tankers and LNG carriers. These four cargo ship types represent the largest proportion of shipping carbon dioxide emissions and account for 89% of global gross tonnage [Buhaug et al., 2009].

Four ship types were chosen to capture the main differences in ship topology. For example, a chemical tanker and a (oil) product tanker have a fairly similar topology and covering both of these ships would not provide any extra fidelity. The ship types and their topology are described in the ship survey that is described in Appendix C.

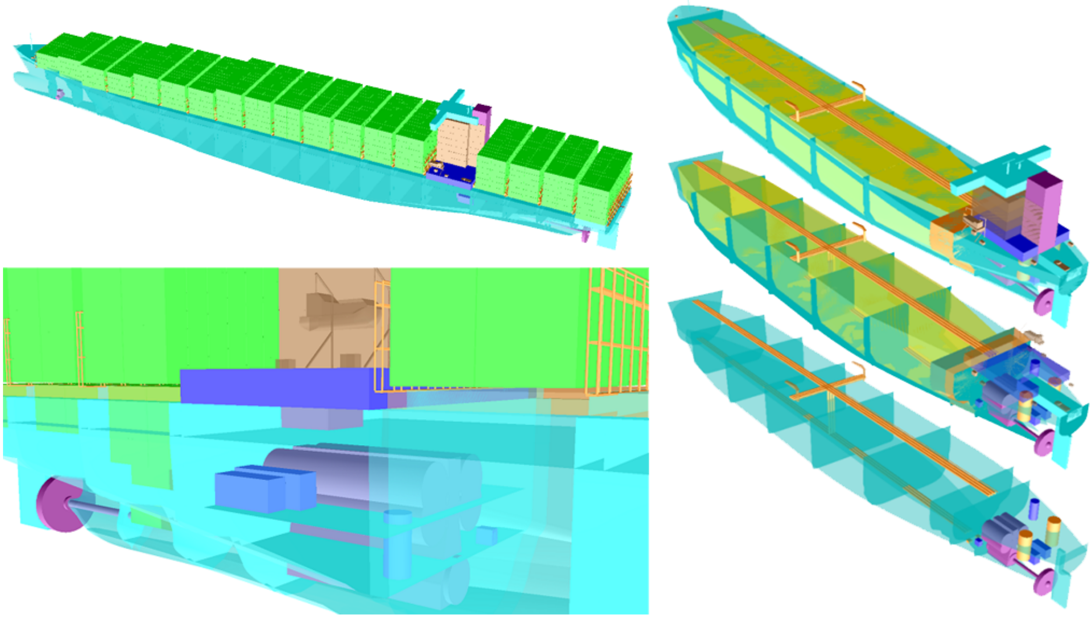


Figure 4.1: Paramarine WSMs of a Post-Panamax container ship (left), showing the detail of the engine room, and an oil tanker (right), showing the complete ship, cargo systems and propulsion machinery .

To find realistic ship and CRT combinations that have a high potential to reduce $CO_2$ emissions, the most commonly used ships were chosen by finding:

- The specification of ships that carry the most in terms of total deadweight.
- The specification of ships that are most widely used (these ships don't necessarily carry the most cargo, but this may allow easier dissemination of new CRTs).
- Ships that cover a wide range of ship types, deadweights and speed.

In total 36 point designs that are different in ship type, size and design speed were chosen that represent international shipping, see Table 4.1, ensuring that they cover a wide range of sizes and the most common configurations. The characteristics of each ship (such as length, beam, draught, displacement, etc.) were picked by selecting specific ships, to ensure the characteristics of the ship are correctly related, rather than averaging all of the ship characteristics. For example, a ship that has the average beam and average length in a size category may have a unrealistic length to beam ratio. This ensures that the potential $CO_2$ emission savings from using different ship and CRT combinations correctly reflect international shipping. The cargo carried, engine size and other parameters were used to check and calibrate the parametric calculations used in the ship design.

| Ship Size Category Name | Displacement Range (to the nearest 1000 tonnes) | 10 knot design speed | 15 knot design speed | 20 knot design speed | 25 knot design speed |
|---|---|---|---|---|---|
| Feeder container ship | around 14 000 te | | C | C | C |
| Handysize bulk carrier | 33 000 - 34 000 te | B | B | | |
| Handymax bulk carrier | around 42 000 te | B | B | | |
| Panamax ships | 71 000 - 73 000 te | B O | C B O | C | C |
| Aframax oil tanker | around 117 000 te | O | O | | |
| Medium-size LNG carrier | around115 000 te | | L | L | |
| Post-Panamax container ship | 122 000 - 123 000 te | | C | C | C |
| Suezmax tanker | 147 000 - 165 000 te | O | O | | |
| Q-flex tanker | 154 000 - 155 000 te | | L | L | |
| Ultra Large Container Carrier (ULCC) | 172 000 - 175 000 te | | C | C | C |
| Cape-size bulk carrier | 186 000 - 188 000 te | B | B | | |
| Very Large Crude Carrier (VLCC) | 305 000 - 343 000 te | O | O | | |

Table 4.1: Selected ship types, sizes and design speeds; C = Container Ship B = Bulk Carrier O = Oil Tanker L = LNG Tanker. There are 36 WSMs in total (32 in the above table and 4 additional LNG carriers to cover two different types of propulsion arrangement). The ship categories were named according to ship type and size and port or canal constraints.

Using Clarksons database [Clarksons, 2010] [Clarksons, 2011] it was found that many ships fall into size categories of similar displacements, possibly due to port and canal infrastructure limitations. LNG tankers are a relatively small proportion of international shipping, but they may represent a growing market because of the potential increase in the use of natural gas as a source of energy. Two types of LNG tankers were also examined, Heavy Fuel Oil (HFO) fuelled two-stroke Diesel propulsion and LNG fuelled steam system propulsion. In 2007 the majority of LNG carriers were steam turbine driven, after 2007 the trend has been towards more Diesel fuelled ships [Noble, 2007]. However, this means there are many steam turbine powered ships currently at sea.

Three loading conditions were examined. The design condition reflects the amount of cargo the ship is going to carry and the ship's top speed so resistance estimates are based on this condition. The ballast condition is important for finding fuel consumption and hence $CO_2$ emissions for ballast legs of voyages, the amount of ballast stored depends upon both stability and propeller immersion. The scantling condition is the heaviest possible load and normally used to size the structure and define the minimum freeboard.

### 4.1.2 Parametric design process

Parametric ship models were built in Paramarine by describing consistent relationships between components as the model is manipulated. For example, changing the engine power changes the size of the engine and the engine length and hence changes the shaft diameter and length, which is modelled based on engine power (in order to calculate shaft diameter) and engine length (in order to calculate shaft length). The shaft maintains its relationship with the engine when the engine is changed to a different size or moved. The relationships between all the aspects of a ship design are inherently complex making the ship design an iterative process. It is important to understand how these relationships change with ship type, ship size and ship design speed and maintain flexibility in the model to make such changes, the use of approximate efficiency or utilisation factors that change according to the ship type are useful for this.

Figure 4.2 shows the ship design process required for each ship size and type. Items in blue are those where a decision is required based on a calculation using ship weight (displacement) or a calculation using one of the other blue items (directly or indirectly). For example, the required bow thruster and engine size are a function of the ship size and weight and the ship size and weight, including the amount of fuel that is required, cannot be determined until the engine size has been selected. The order in which the blue iterative items are carried out is not normally important, although it is possible to complete the iterations quickly by starting the iterations by only iterating the items that have a larger impact on the displacement and volume of the ship.

The design process shown in Figure 4.2 shows the parts of the WSMs that are iterated and/or require inputs from the user. The other parts of the model that are not shown are automatic, for example, upon selecting the required engine size to meet the power requirement the engine mass and volume are automatically updated by referring to a list of engines. The model calculates the weight and volume of all of the components of the ship, following the users iterations, these are added and compared to the buoyancy and volume of the overall ship in order for the user to balance the design by iterating the items in blue. This is a fairly conventional ship design spiral [Watson, 1998].

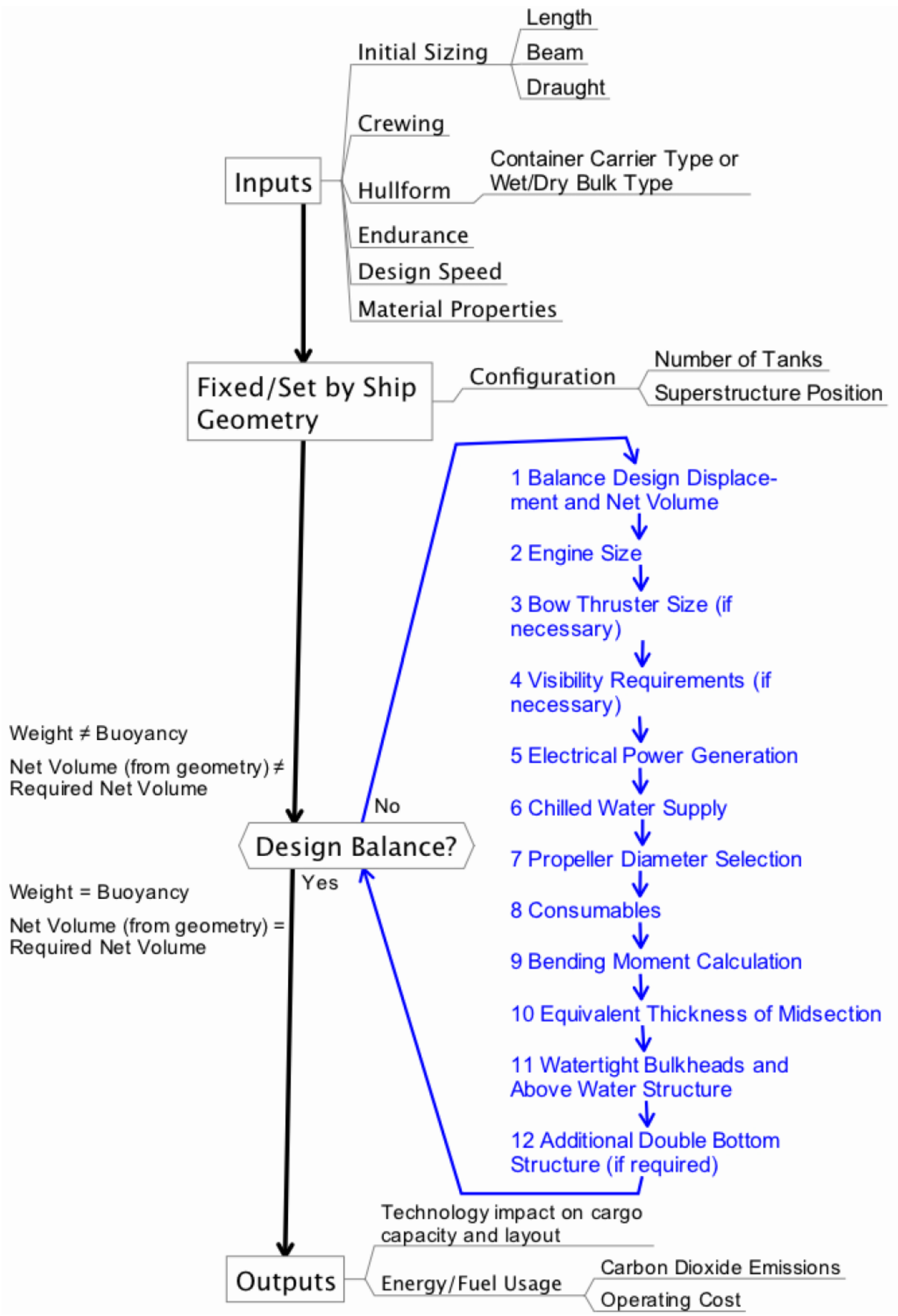



Figure 4.2: User design procedure for the iterative Whole Ship Model (WSM).

#### 4.1.2.1 Future marine technological development

In order to consider potential future changes in the design speed of the hull form, ship models were made at one or two additional design speeds. For instance slower 15 and 20 knot container ships and 10 knot oil tanker hull forms were designed by manipulation of the extent of the parallel mid-body and bilge radius in order to get the hull shape coefficients, such as prismatic coefficient and block coefficient. Slower fuller hull forms potentially have less $CO_2$ emissions per unit cargo carried due to the increased cargo carrying capacity outweighing the loss in through water performance, this is especially the case at lower Froude numbers. This is similar to the Maersk Triple-E that has a fuller form compared to Emma Maersk Class [RINA, 2011].

## 4.2 Implementation of Liquid Natural Gas (LNG)

*As an important CRT within the LCS project a study on LNG fuelled propulsion was carried out. The work carried out on the implementation of LNG as a fuel on ships was initially carried out and presented in two conference papers [Calleya et al., 2011a] [Calleya et al., 2011b] and has since been updated following feedback from industry and academia. See the list of publications in Appendix D.*

Figure 4.3 summarises the main considerations and energy flows for the use of LNG as an energy source. The left of Figure 4.3 shows leakages and Boil Off Gas (BOG). BOG is from the evaporation of LNG stored in tanks and can be used as an engine fuel (shown by the black dotted arrows).

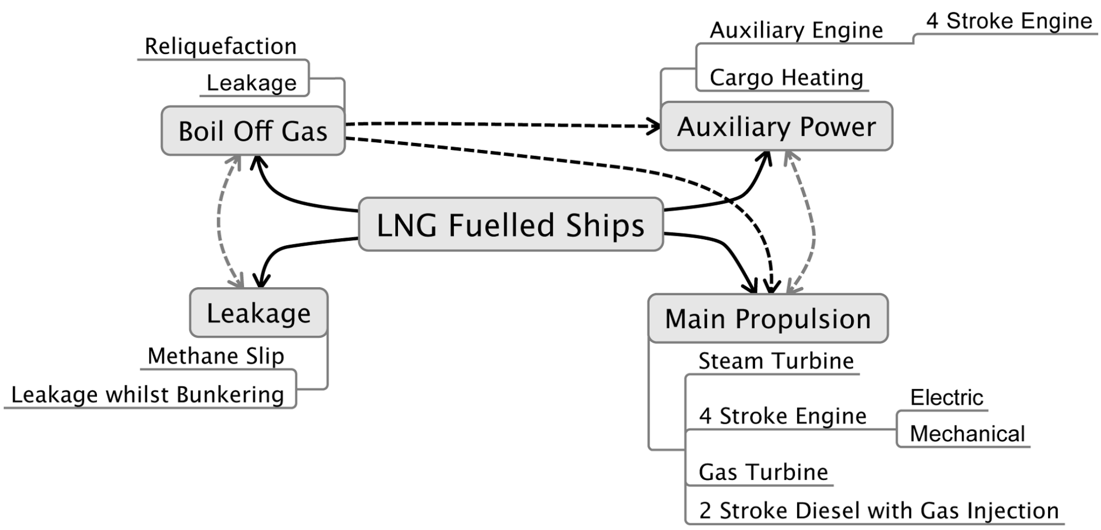



Figure 4.3: Flow of energy from LNG as a fuel and possible usages [Calleya et al., 2011b].

When examining different options for natural gas propulsion and storage some references have been made to LNG carriers. Since 1964 a number of LNG carriers have been in operation using Boil Off Gas (BOG) as fuel for the propulsion machinery [Einang and Haavik, 2000].

### 4.2.1 Main propulsion

As mentioned in Section 3.4.3.3, steam turbines have been used on LNG carriers since the 1960's and are well proven and reliable. However the maximum efficiency of the steam propulsion system is approximately 30% at full load and this gets lower as the turbine load goes down [Yeo et al., 2007]. An advantage of a steam propulsion system is that boilers can be fuelled by both a gas (from boil off gas) and liquid fuels.

In 2008, approximately a quarter of LNG carriers were using two-stroke Diesel fuelled engines with re-liquefaction [Chang et al., 2008]. A two-stroke Diesel fuelled engine with re-liquefaction may be more efficient than using four-stroke dual-fuel engines, with electric propulsion, especially for high capacity and long-range LNG carriers [Yeo et al., 2007]. Another quarter of LNG carriers were using four-stroke dual-fuel engines, with electric propulsion, with the remaining half of the market using steam turbines [Chang et al., 2008]. The trend for new builds is towards two-stroke and four stroke engines, steam turbines for LNG carriers are likely to be phased out.

Four-stroke dual-fuel engines have so far required a small smount of Diesel fuel for ignition as well as accurate monitoring and electrical control of each cylinder [Yeo et al., 2007].

Following an initial container ship concept in 2011 containing a two-stroke natural gas engine [DNV and MAN, 2011], MAN now offers two-stroke dual-fuel engines, designated as ME-GI [MAN, 2013]. The first commercial order for the two-stroke ME-GI was in 2012, by Teekay for LNG carriers constructed by Daewoo Shipbuilding & Marine Engineering (DSME) of South Korea for delivery in 2016 [MAN, 2012a].

Wärtsilä also provides two-stroke dual-fuel engines, which are designed to use gas at a low pressure (smaller than 10 bar) using the Otto cycle [Wärtsilä, 2013b]. The MAN ME-GI engine delivers gas to the engine inlet at a high pressure (250-300 bar) [MAN, 2013] and uses the Diesel cycle [Wärtsilä, 2013b].

Methane slip (see Section 4.2.5) may be more likely with low pressure engines [Einang, 2011]. Both low pressure and high pressure dual-fuel engines also require oil-based fuel for ignition [MAN, 2013] [Wärtsilä, 2013b]. Spark-ignition gas engines (for example, the four-stroke

Bergen B and Bergen C engines from Rolls-Royce Bergen) can provide a higher efficiency at high load compared to dual-fuel Diesel engines. [Einang, 2011]. Though dual-fuel engines are less efficient than spark-ignition gas engines they do offer additional redundancy [Calleya et al., 2011b].

Two-stroke engines are much more efficient than steam turbines, which have a efficiency of approximately 30% at full load [Yeo et al., 2007] (see Sub-subsection 3.4.3.3), and thus are a very likely form of propulsion using natural gas in the future. It is also possible to convert existing engines to run on natural gas [Einang, 2011]. For larger vessels the larger two-stroke engines being offered by MAN and Wärtsilä allow a direct drive mechanical propulsion system to be used, preventing the transmission and conversion losses present in electrical systems [Yeo et al., 2007].

### 4.2.2 Auxiliary power, shaft generator and waste heat recovery

Four-stroke engines are normally used for auxiliary power and can be converted to dual-fuel gas engines or replaced with dual-fuel or spark-ignition gas engines. Ship boilers can be converted to natural gas by replacing or modifying the burners.

In general, a ship that uses a large two-stroke dual-fuel engine is likely to use a shaft generator (PTO) when underway to generate electricity because this is more efficient than a smaller four-stroke dual-fuel engine. However, a ship carrying both natural gas and Diesel may want to prioritise the use of one fuel other another depending on emission regulations (for example, if transiting through a ECA) or in order to use the Boil Off Gas (BOG), this is discussed further in section 4.2.8.

When using natural gas in internal combustion engines waste heat recovery is likely to be used in the same way as it is for oil-based fuel internal combustion engines, though the exhaust and jacket water temperatures will be different.

The implementation of most other CRMs is likely to remain largely uneffected by the use of natural gas as an alternative to oil-based fuels.

### 4.2.3 LNG or CNG?

It is usual practice to store natural gas at atmospheric pressure at -163°C [Moon et al., 2005]. Natural gas remains at the boiling point for the pressure at which it is stored (normally atmospheric pressure) because as the vapour boils off the heat that is required for the phase change cools the remaining liquid allowing it to stay at the same temperature. Depending on how effiicient the insulation is, only a small amount of boil-off is necessary to maintain the temperature of the liquid. For a LNG carrier boil-off liquid is approximately 0.1% of cargo per day [Chang et al., 2008].

Natural gas can also be stored at a pressure between 100 and 275 bar as Compressed Natural Gas (CNG), to achieve energy densities of approximately a third of that of LNG [Young and Eng, 2007].

Though CNG may be justified on gas carriers to exploit smaller less contiguous reserves where the investment and energy used in liquifaction facilities cannot be justified [Young and Eng, 2007], CNG remains very unlikely to be adopted as a fuel on large ships because of its very low energy density [Calleya et al., 2011b].

It is also worth noting that gas storage pressures higher than 10 bar have to be individually certified and approved [Det Norske Veritas, 2011a] [Germanischer Lloyd, 2010].

### 4.2.4 Classification society regulations

Det Norkse Veritas (DNV) and Germanischer Lloyd (GL) regulations for gas fuelled ships are very similar and are based upon, or refer to, established rules for gas carriers [Det Norske Veritas, 2011a] [Germanischer Lloyd, 2010].

The regulations are to ensure that gas storage, machinery spaces, piping arrangements, bunkering and ventilation are protected from both the leakage of gas and sources of vapour ignition [Germanischer Lloyd, 2010].

For gas only installations, where there is no secondary fuel supply, the fuel storage should be divided between two or more tanks located in separate compartments [Germanischer Lloyd, 2010]. This may make the regulations easier to adhere to for dual-fuel installations compared to gas only installations.

Gas storage tanks should also be located as close to the centreline as possible and away from the ships side and bottom plating [Det Norske Veritas, 2011a] [Germanischer Lloyd, 2010]. Compressed and liquified gas storage on open deck is allowed providing tanks are $Beam/5$ away from the ships side and have adequate natural ventilation [Germanischer Lloyd, 2010]. Placing gas storage tanks on deck can negate the need for dedicated ventilation.

### 4.2.5 Barriers to adopting LNG

LNG is a relatively recent energy option for ships when compared to oil based fuels with most of the initial experience being based upon LNG carriers. The main barriers to implementation of LNG as a fuel are (adapted from [Calleya et al., 2011a]):

- New regulatory and safety requirements for a cryogenic fuel.
- Lack of bunkering infrastructure and technology for handling natural gas in ports.
- "Well to propeller" $CO_2$ emissions for LNG are likely to be higher than for HFO, especially if renewable sources are not used for liquefaction. As mentioned in Subsection 3.6.1, marine transportation routinely uses residual fuel, both a waste product of petroleum refining and a blended product itself [Winebrake et al., 2006].
- Not a long-term solution; natural gas is a non-renewable resource.
- Current and Future profitability is uncertain; natural gas has a similar price sensitivity to oil (especially if natural gas becomes more widely adopted)
- Additional crew training.
- "Methane slip" (unburned fuel in the atmosphere) and leakage (during bunkering) - methane is 21 times more potent a GHG than $CO_2$ on a per-tonne basis [Sustainable Shipping, 2011].

A further area of current development in LNG is bunkering technology and solutions. The refuelling process for LNG is complex when compared to conventional oil-based liquid fuels because LNG tanks have to be kept at a very low temperature. This requires additional systems in order to carry out inert gas purging and pre-cooling of the tanks before fuelling [Lamb, 2004]. LNG carriers avoid having to re-cool LNG tanks after unloading by keeping some LNG in the tank, this is referred to as "heel", in order to keep the tank cool. When using LNG as a fuel it is envisaged a similar practice can be used, though this will reduce the amount of usable LNG in a LNG tank. There does need to be support for inert-gas purging and cooling of tanks. This equipment may be better provided near bunkering stations in ports rather than being fitted to all ships.

### 4.2.6 Layout and arrangement of LNG tanks and support equipment

The tanks, equipment and machinery for LNG were added to the WSMs for each ship type in order to examine different arrangements that meet the required regulation and maximise cargo. The location of LNG tanks is the main consideration.

The volume of the LNG tanks normally has a bigger impact on a ship than the mass. When the tanks were located in the cargo holds the volume of the tanks displaced the equivalent volume of cargo. As a container ship has lower density cargo compared to a oil tanker or bulk carrier, a smaller mass of cargo was displaced from the container ship by the tanks so the container ship performed slighly better in terms of the tonnes of $CO_2$ emitted per tonne of cargo.

Cuboid shape tanks have better volumetric efficiency. For similar reasons, in LNG carriers membrane tanks are normally preferred due to being capable of loading 8% more cargo than a spherical tank type LNG carrier with identical principal ship dimensions [Moon et al., 2005].

Sloshing in tanks, particularly in square tanks, is a potentially a problem on LNG carriers. Sloshing can damage tanks, possibly increase BOG and effect the stability of a ship. This is not envisaged to be an issue when using LNG as a fuel because the LNG tanks are much smaller compared to a LNG carrier.

The layout requirement for LNG fuel tanks to be $Beam/5$ from the ships side is inconsistent with LNG tankers. On LNG tankers the distance between the tank and the outer side shell is driven mostly by the insulation requirements and is relatively narrow (the midship section and side wall thickness of different ship types can be seen in Figure 5.1). Additionally, when carrying LNG as a cargo no LNG can be stored below the superstructure, so there was some clarification needed as to whether this would be allowed for LNG fuelled ships. In 2012, it was shown that it is possible to classify a ship that uses LNG as a fuel stored under the superstructure when a 9000 TEU container ship design by Kawasaki Heavy Industries obtained an “approval in principle” from Det Noske Veritas [Det Norske Veritas, 2012]. Holistic safety assessments may be required for approval, especially considering some types of LNG fuelled ships are likely to operate closer to people and in more crowded waters than LNG carriers do.

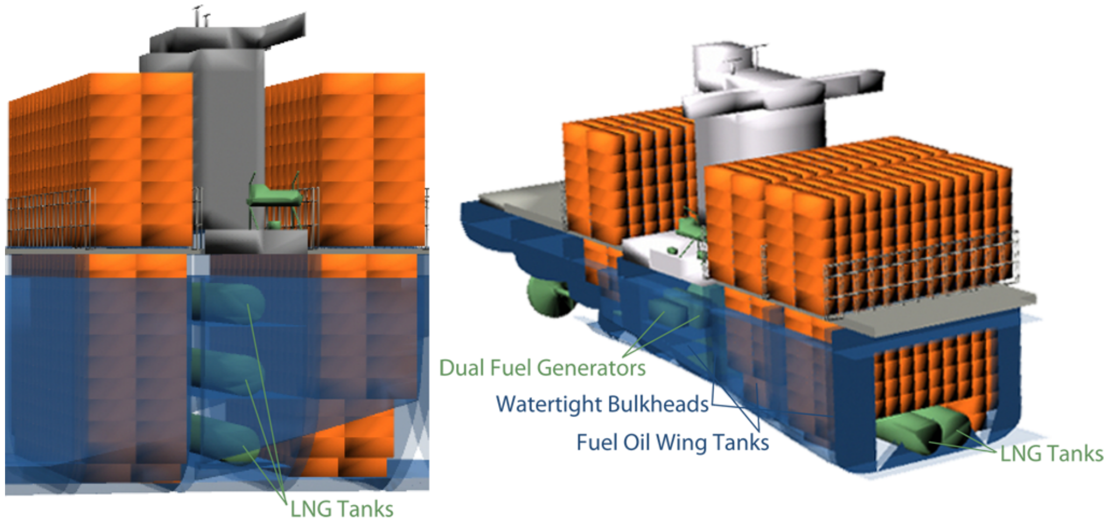



Figure 4.4: Different LNG tank arrangements are possible for different ship topologies.

As shown in the right of Figure 4.4, the cargo hold forward of the forward engine room bulkhead was used to locate LNG tanks. This separates the LNG tanks from the machinery spaces, using a main bulkhead as a divide between propulsion machinery and sources of ignition. This also allows for shorter pipes between the LNG fuel tanks and the engines. The arrangement of tanks changes with the topology of the ship. For ultra large container carriers (ULCCs) with a twin superstructure arrangement it may be beneficial to place LNG tanks under the forward accomodation superstructure. As depicted in the left of Figure 4.4.

The LNG tank arrangement shown in the right of Figure 4.4 was assumed for all ship types. This, pessimistically, assumes that the LNG tanks impact on cargo. Cylindrical LNG tanks, IMO Type C tanks, placed on the deck of a ship are likely to be preferred for the following reasons:

- Space is less of a issue on the deck of some ships, particularly for bulk carriers, this allows for the use of cylindrical tanks that are more structually and volumetrically efficient than prismatic or cuboid shaped tanks.
- Having LNG tanks on deck means may mean that the volume in the cargo holds of the ship can be maintained.
- There may be adequate natural ventilation on deck.
- Likely to be separated from propulsion machinery and sources of ignition by at least one deck, however there may also be some disadvantages to this, such as longer pipes.

Alternatively, for large container ships LNG tanks could be located either side of the main engine or as containerised LNG tanks on deck, as illustated by a Levander and Sipilä [2008]. Having containerised LNG tanks may provide a way to improve bunkering time by allowing for flexibility in the amount of LNG that is carried, though containerised LNG tanks for use as a fuel may require additional safety considerations, particularly concerning how the containers are secured.

There is at least one instance of a large container ship being converted to run on LNG for auxiliary power using LNG from containers on deck [Det Norske Veritas, 2010a].

### 4.2.7 Results from initial study

The initial results, shown in Table 4.2 were based on steam turbine propulsion because that is what data was available at the time of the study, this is a pessimistic estimate of performance because two-stroke dual-fuel engines are much more efficient and were later included in the modelling process.

Table 4.2 shows what the price of LNG should be relative to oil in order to have the same fuel cost as an oil fuelled ship, as the future price of LNG is uncertain. For example, in Table 4.2 for a 15 knot oil tanker that uses LNG for both propulsion power and auxiliary power (designated by the both column) the price of LNG would have to be 1.07 times the price of oil to have a LNG fuelled ship that has the same fuel cost as an equivalent oil fuelled ship. If the price of LNG is less than 1.07 times the price of oil it may become financially viable to specify a new ship with LNG instead of oil, though this also depends on the additional purchase costs (mainly LNG tanks and systems), which have not been included in this comparison.

| Panamax ship type | Oil tanker | | Bulk carrier | | Container ship |
|---|---|---|---|---|---|
| Design speed | 15 knots | | 15 knots | | 25knots |
| How LNG is used | Auxiliary | Both | Auxiliary | Both | Auxiliary |
| £LNG/ £Oil | 0.95 | 1.07 | 1.26 | 1.13 | 0.88 |
| Oil Used (te/day) | 17.01 | 0.00 | 17.01 | 0.00 | 118.75 |
| LNG Used (te/day) | 6.41 | 25.45 | 2.42 | 21.47 | 9.87 |
| $CO_2$/Cargo (te/te) | 0.0014 | 0.0013 | 0.0011 | 0.0010 | 0.0114 |
| EEDI | 6.03 | 5.96 | 5.96 | 5.89 | 42.90 |

Table 4.2: Summary of Fuel Costs, Fuel Consumption and EEDI from initial study on using LNG as a fuel [Calleya et al., 2011b].

Panamax ship sizes were chosen because Panamax size ships, in terms of the number of ships, are likely to be the most common single size category, with over 30% of bulk carriers and container ships being Panamax size, see Appendix C.

In the final model MAN ME-GI two-stroke engines [MAN, 2013] were used with Wärtsilä generating sets [Wärtsilä, 2013a]. For smaller amounts of LNG storage Wärtsilä LNGPac tanks [Karlsson and Sonzio, 2010] were used and TGE Marine (in partnership with MAN) tanks were used for storing large amounts of LNG.

A space is also required for equipment to support the tank and pipe the natural gas to the engines, this may contain a compressor, this depends on the engine and engine pressure required, however the impact of this space on a ship, in terms of weight and space, is small. A natural gas only powered vessel negates the need for a Diesel settling tank and this would likely outweigh the impact of a tank room.

Figure 4.5 shows the variation in $CO_2$ emissions with operational speed for the oil tanker (that is designed for a speed of 15 knots). Above 10 knots $CO_2$ emissions increase more drastically because wave-making resistance drastically increases the amount of power required. Ship size was found to have no impact on the $CO_2$ emission reduction potential of natural gas and there did not appear to be any benefit from carrying different proportions of natural gas and oil [Calleya et al., 2011b].

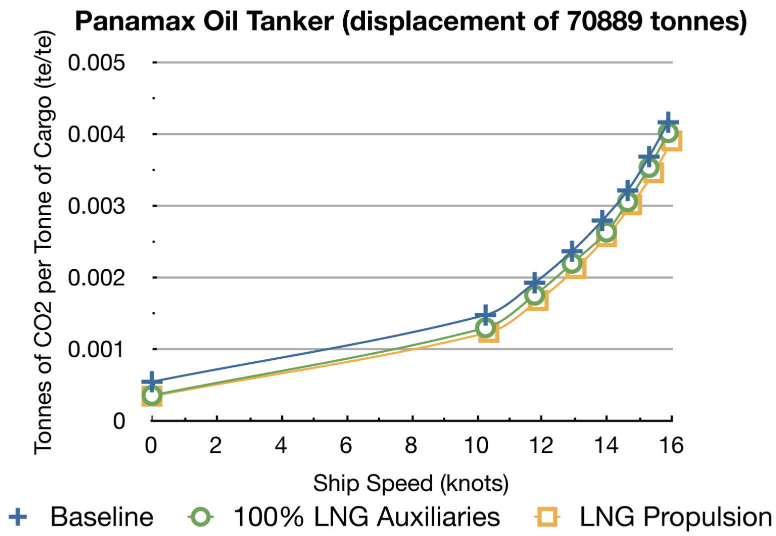



Figure 4.5: Examining the change in operational speed for a Panamax oil tanker with a design speed of 15 knots [Calleya et al., 2011b].

### 4.2.8 Boil Off Gas (BOG) and leakages

For LNG carriers with more than 200 000 $m^3$ capacity a re-liquefaction plant could require up to 6 MW of electric power [Hansen and Lysebo, 2006]. In most cases an energy intensive re-liquefaction plant for BOG can be avoided as long as the LNG tanks have a high enough working pressure to allow BOG to build up due to periods of no engine operation.

There is a possible economical advantage to the re-liquefaction of BOG [Lamb, 2004] in LNG carriers, with BOG being approximately 0.1% of cargo per day [Chang et al., 2008]. However, when using LNG as a fuel:

- The BOG will likely be used at a faster rate than it is occurring.
- A re-liquefaction plant may require a lot of energy negating the benefits of using LNG as fuel when compared to oil.

In order to demonstrate that the BOG will likely be used at a faster rate than it is occurring, consider using LNG for auxiliary power only on a Panamax container ship, used in this initial study [Calleya et al., 2011b], it has an installed auxiliary power requirement of 8262kW (this compares to 8150kW for the baseline HFO ship). The LNG ship emits approximately 10.4 tonnes of $CO_2$ per day less than the baseline HFO ship. To meet the energy requirement over the voyage the ship carries 346 tonnes of LNG, if the BOG occurs at a rate of 0.1% [Chang et al., 2008] per day, that is 0.3 tonnes of BOG generated a day. The ship uses approximately 3.8 tonnes of LNG per day this is larger than 0.3 tonnes of BOG that has been generated so all the BOG can be used. This is a simple calculation and does not account for fluctuations in power or methane slip and other leakages, but on average the difference between the LNG used and the BOG is large.

### 4.2.9 The impact on the Energy Efficiency Design Index (EEDI)

The calculated EEDI was compared against the actual emissions using an assumed operating profile. The assumptions in EEDI mean that there is a difference between design for EEDI and design for low emissions. EEDI is a measure of transport efficiency [IMO, 2009c], but is simpler than calculating the actual transport efficiency based on an operating profile. An overview of different current regulatory measures is in Subsection 2.4.2.

The EEDI defines deadweight as the maximum possible cargo capacity and 65% of the maximum for a container ship [IMO, 2009c], this gives a smaller ratio of fuel consumption and $CO_2$ emissions to cargo. In operation the average speed is likely to be lower than the design speed and the cargo capacity will be less than the maximum. Design speed has the single biggest effect on EEDI due to much large increases in installed power required at higher speeds, the speed to power relationship is shown in Figure 4.5. The EEDI also includes a fixed calculation for auxiliary power [IMO, 2009c]. This benefits ships with a smaller auxiliary power changing to natural gas.

### 4.2.10 Costing considerations

When the first LNG powered ferry was designed and constructed in Norway the purchase cost was around 30% more than an equivalent Diesel fuelled ferry [Einang and Haavik, 2000]. However, this was over a decade ago and it is possible that the costs are now more similar to conventional marine Diesel engines. Without detailed costs available in terms of tanks, engines and support equipment; the final costs that were used in the model assumed that implementing LNG requires an additional Unit Purchase Cost (UPC) of $125 per kW on the combined installed power of the main engine, auxiliary engine and boilers. This is when compared to a conventional Diesel fuelled baseline ship.

### 4.2.11 Further considerations and conclusions

The study has confirmed that the potential reduction in $CO_2$ emissions from LNG is significant when compared to other CRTs, in Section 3.7. LNG may be a viable energy option in the future. However, if the $CO_2$ emissions from the entire lifecycle of LNG are considered, including the losses due to methane slip and the energy required for liquefaction of natural gas, then LNG may not be a good replacement for residual fuels, which would otherwise be discarded. As a ship has a lifetime of, typically, over 20 years and the future cost differential between natural gas and oil-based fuel is not clear it is important to mitigate the consequences of a wrong decision. By using LNG only for auxiliary power the reduction in overall ship $CO_2$ emissions are still in the region of 10% [Calleya et al., 2011b], therefore depending on how LNG is implemented and how the $CO_2$ emissions are calculated $CO_2$ emission reductions of at least 10% are possible, possibly up to around 20%. Accounting for reduced cargo capacity due to carrying LNG can have a 1% to 2% difference on the calculated $CO_2$ emission reductions. On ballast legs and when the full capacity of the ship is not needed the impact on cargo is less significant.

The current regulatory incentive for investing in natural gas for ships in operation is because natural gas has significant reductions in $NO_x$, $SO_x$ and PM emissions when compared to oil [RINA, 2010c], this is especially useful if the ship has to operate in an ECA or a port that has strict emission controls and can ensure that a vessel is ready for future emissions regulation, such as IMO Tier III $NO_x$ emissions.

Although the implementation of LNG as a fuel will change depending on the specific ship topology that is being examined the potential $CO_2$ emission reductions are high. Generally when implementing LNG into a ship:

- The endurance/range of a vessel may be an important consideration when considering changing fuels. This is because LNG tanks can potentially have a large impact on a ship requiring a lot of volume.
- Re-liquefaction is unlikely to be required when using LNG as a fuel.
- The calculated $CO_2$ saving is insensitive to ship size [Calleya et al., 2011b].
- The calculated percentage $CO_2$ emission reduction on the overall ship could decrease with increasing speed as a larger amount of LNG storage impacts on the cargo capacity of the ship [Calleya et al., 2011b].

In this Thesis we consider the operational $CO_2$ emissions from the ship, as mentioned in Subsection 1.2, the boundaries for the system that is being analysed can change the answer. In the case of the fuel infrastructure of LNG and HFO, as they are currently manufactured, the "well to propeller" $CO_2$ emissions of LNG (not included in this study) are likely to be higher than for HFO, especially if renewable sources of energy are not used for liquefaction. In order to understand the full impact of switching to alternative fuels, consideration of the through-life $CO_2$ emissions is important [Calleya et al., 2011b]. Especially considering that marine transportation routinely uses residual fuel, both a waste product of petroleum refining and a blended product itself [Winebrake et al., 2006].

## 4.3 Implementation of Wind

Wind energy can be used to generate electricity, via a wind turbine, or to save fuel and/or increase speed, via sails or magnus-effect devices. The different ways of using wind energy that are summarised in literature [Bergeson and Greenwald, 1985] [Clayton, 1987] can be represented in five categories; hard (wing) sails, soft sails (could be different rig configurations such as a square rig or fore and aft reg), Flettner rotors, wind turbines and kites. These are illustrated in Figure 4.6.

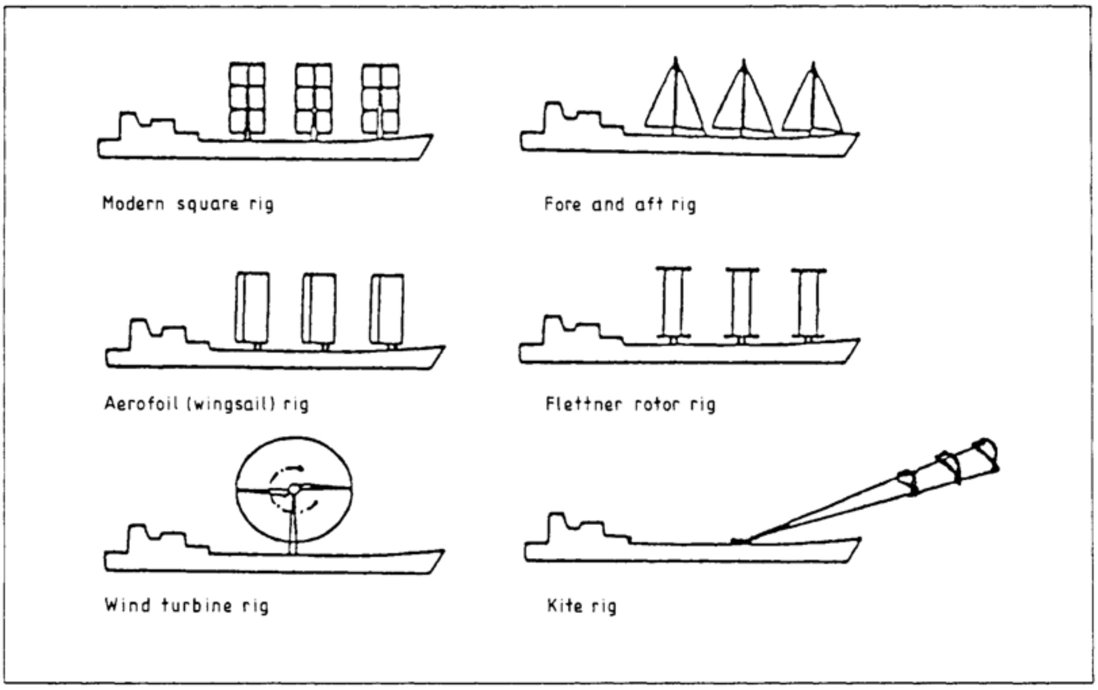



Figure 4.6: Different wind rigs for ships [Clayton, 1987].

Different types of rig have different lift and drag coefficients with different wind angles. This means that a particular rig may be better suited to a particular journey and a mixture of different types of sails on the same ship may potentially offer some advantage [Clayton, 1987].

Figure 4.7 shows that as well as producing a thrust in the direction of the ship, sails will also produce a side force, $S$, that is balanced by a hydrodynamic side force causing a helling motion. For smaller ships this angle may be up to 5 degrees [Clayton, 1987]. The hydrodynamic forces that balances the force from the sails also causes a yaw moment. The yaw moment from all sails and kites may need a rudder correction that increases resistance [Naaijen et al., 2006].

No fuel saving are obtained for upwind conditions [Naaijen et al., 2006]. Sailing ships have to sail at an angle to the wind and tack (constant change of direction to keep on course and at an angle to the wind) when sailing upwind.

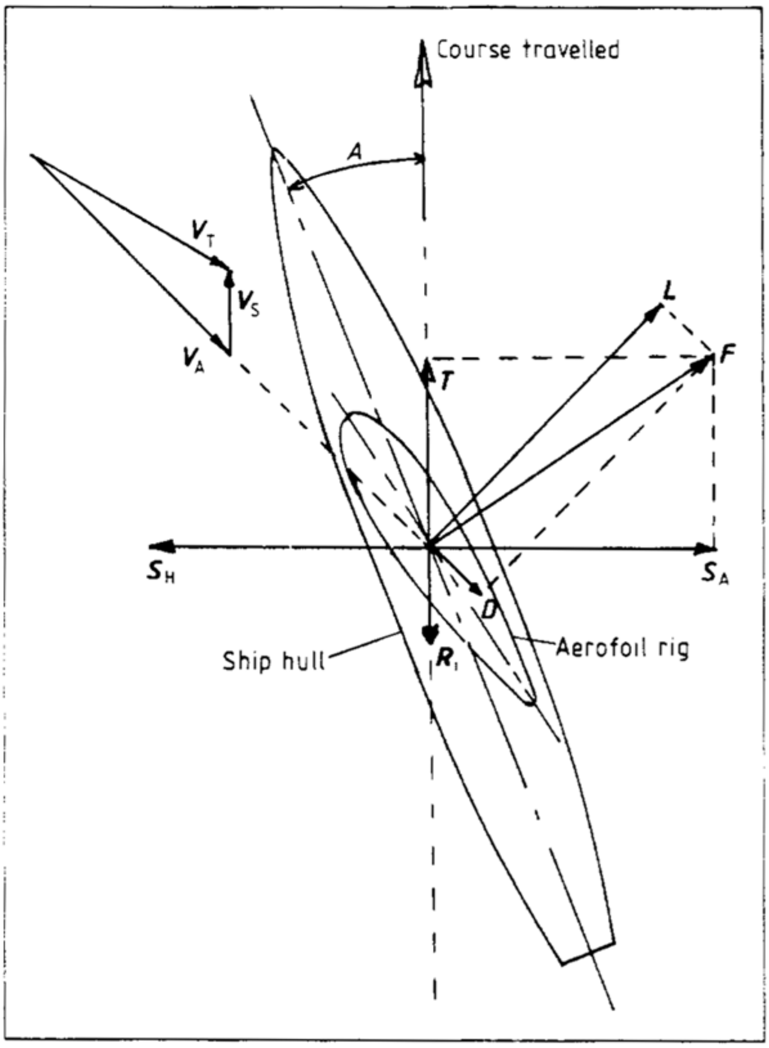



Figure 4.7: Forces and velocities on a wind rig [Clayton, 1987].

### 4.3.1 Kites

Kites have the following features when compared to sails:

- Can access higher altitudes with higher wind speeds [Naaijen et al., 2006].
- Have no stability or visibility problems associated with high masts [Naaijen et al., 2006].
- Losses due to drift, rudder angle and off-design operation are small and are counteracted by an improved open-water efficiency (placing the kite attachment as far forward on the bow as possible reduces the required rudder correction) [Naaijen et al., 2006].
- Kites require deployment and recovery mechanisms [Hochkirch and Volker, 2010].
- Have minimal impact when not deployed, both on cargo handling and in air draught.
- The velocity of the kite can be increased by moving it on a desired course, sometimes a complex figure of eight motion [Naaijen et al., 2006] [Clayton, 1987].

### 4.3.2 Wind rig selection

Sail assisted propulsion, sails in conjunction with a Diesel engine, is often employed to allow the ship to operate effectively in all conditions [Bergeson and Greenwald, 1985], as mentioned in Subsection 3.4.4.

The flow around sails is complex, especially around soft sails where mast shape becomes very important, as that is where some flow separation can occur [Crook et al., 2002]. The variation in wind speed and direction with altitude can also be significant. The variation in wind speed with altitude can be expressed by a logarithmic profile [Crook et al., 2002]. Sail twist is used in sailing, where the head of the sail is at a different angle of incidence from the foot of the sail in order to change the lift distribution with height.

Wing (hard) sails were found to be the best performer overall from two different studies that compared different wind rigs [Clayton, 1987] [Bergeson and Greenwald, 1985]. Wing sails are shaped more like aerofoils, they appear to be capable of producing higher lift coefficients [Bergeson and Greenwald, 1985] and may allow sailing closer to the wind than soft sails.

### 4.3.3 Ship design considerations

In order to maximise the potential of sails some aspects of the operating procedure and some operational CRMs, such as weather routing (mentioned in Subsection 2.6.2), need to change considerably. Additional ship design and operational considerations are required for the implementaion of sails.

Ship design considerations:

- Stability considerations for masts and sails; examine a number of different conditions with masts in different states.
- Structural considerations for masts and sails; depending on how the masts are integrated they could increase the still water bending moment of the ship as well as impact on the local structure.
- Determine sail area from a compromise between the thrust from the mildest wind force and stability and structural considerations.
- Need to understand how lift and drag force varies with angle of attack. Drag coefficients are normally obtained experimentally [Clayton, 1987].
- If possible minimise the rudder corrections required due to the side force, $S$, on the sails.
- Engine size could be reconsidered, although having smaller installed power available for propulsion may not be adequate for all weather conditions and may reduce sea margins.
- Propeller performance and engine and propeller matching requires careful consideration because for a given speed the propeller provides an amount of thrust that is dependent on how much thrust is being provided by the sails.
- Sails should not be too obstruct bridge visibility too much (especially in light winds).
- Consider clearences required for bridges and port handling equipment; impact on cargo handling and other deck activities should be minimised.
- Ability to quickly reduce load on sails in an emergency. Manual emergency furling systems could also be installed [Perkins et al., 2004].

Operational considerations:

- Using wind energy would be difficult for stopping and manoeuvring in port. Sails cannot be used for transiting in tight areas [Nijsten and de Vos, 2002].
- May require additional crew training, which has a associated cost.
- Changes in operational procedure are required to maximise the potential energy from the wind. For instance, when tacking on larger ships the foremast tacks first while the other masts stay in position, for smaller sailing ships the momentum carries the ship through the wind [Perkins et al., 2004].

The ship design considerations and operational considerations have been separated by whether they primarily effect the ship design or the ship in operation. However, the operational considerations can impact on the ship design and the ship design considerations can impact on the operation of the ship.

Though existing ships can be retrofitted with sails a higher potential reduction in $CO_2$ emissions is likely from designing a new ship [Bergeson and Greenwald, 1985]. For example, the hull form could be designed for sails possibly to reduce the rudder corrections required due to the side force $S$ or to make it easier for the ship to tack.

### 4.3.4 Procedure and results of initial study

The performance of wing sails on an oil tanker with a constant heading and speed of 15 knots was examined. Wind data for a north Atlantic crossing was used [Gibbons-Neff and Miller, 2011] which defines force 4 (14 knot) wind in varying directions. The lift and drag coefficients for wing sails were taken from experimental data for wing sails [Bergeson and Greenwald, 1985].

Some assumptions were made to simplify the analysis and allow for the ship and sail to be modelled:

- Constant ship speed.
- No change in propulsion coefficient due to sails, generating thrust from the wind will reduce the loading on the propeller.
- No secondary benefit of reducing engine size (if possible, may need to maintain constant speed without sails).
- No consideration of sway force and yaw moment from the sails that will cause a heeling angle.

- The sail is always at the best angle of attack and does not take time to move to different angles of attack.

- It was assumed that the ship only travelled in one constant direction - further saving may be possible over a voyage by changing course to coincide with wind direction.

The variation in lift and drag coefficients with the angle of attack of the sail was considered. For each wind direction (nine including calm weather) the thrust was calculated at different angles of attack and the highest was chosen. These results were then multiplied by the percentage of time spent in each weather and wind direction to find the overall average thrust.

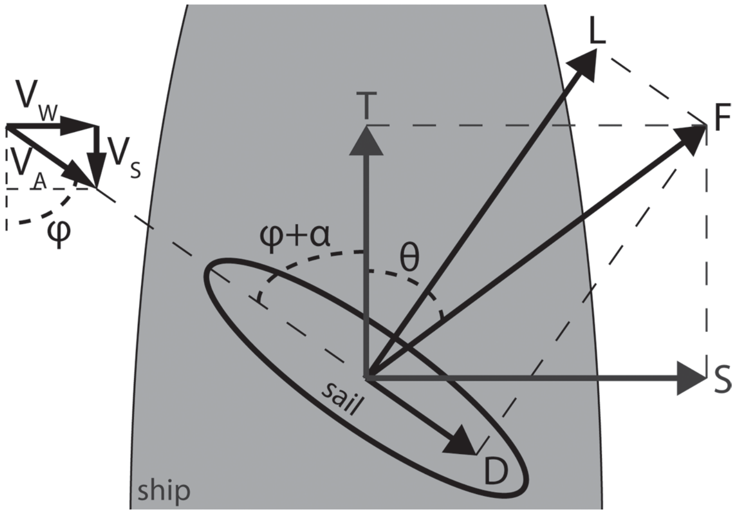



Figure 4.8: Forces and velocities on a sail and ship (adapted from Clayton [1987]).

A force and velocity diagram for a wing sail and a ship is shown in Figure 4.8. The procedure for calculating the thrust, $T$, from a given wind velocity and ship velocity, $V_W$ and $V_S$, for each angle of attack, $\alpha$, is:

1. Find the apparent wind angle, $\phi$, and velocity, $V_A$, relative to the ship from the wind velocity, $V_W$, and the ship velocity, $V_S$.

2. Calculate the Lift, $L$, and Drag, $D$, forces due to the sail, considering the angle of attack of the sail, $\alpha$.

3. Calculate the resultant Force on the sail, $F$, and angle of attack, $\theta$ (that is using $F = \sqrt{D^2 + L^2}$ and $\theta = 90^\circ - (\alpha + \phi) + \arccos(L/F)$).

4. Resolve the forces in the direction of the ship, $T = F \cos \theta$.

The above process is repeated for each angle of attack, $\alpha$. The angle of attack $\alpha$ that gives the highest thrust in the direction of the ship, $T$, is selected. It could be better to iterate $\alpha$ to find the highest thrust in the direction of the ship, $T$, especially if computational time is important, but in this case a number of angles of $\alpha$ convering all directions were considered. The effect of the side force, $S$, was not considered.

Figure 4.9 depicts the arrangement of 1607m$^2$ of sails that was fitted to a Panamax oil tanker by considering a required clearance between each sail and the deck. The best arrangements will likely have fewer and taller rigs to capture highest wind speeds at higher altitudes and reduce interference between rigs. In this case the interference between the sails was not considered because this is not easy to estimate so the main purpose of the Whole Ship Model (WSM) was to approximate the sail area. A Panamax size ship was chosen because Panamax size ships are the most common single size category, with over 30% of bulk carriers and container ships being Panamax size, see Appendix C.

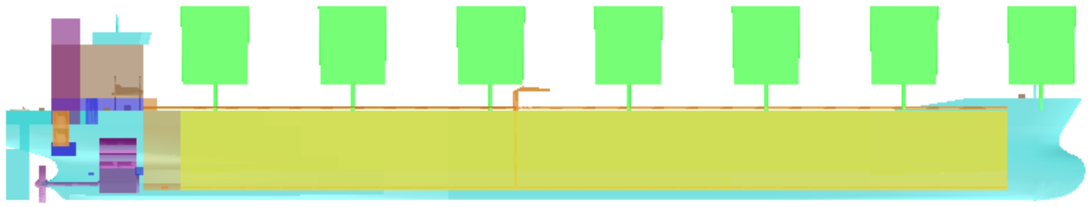


Figure 4.9: Wing sail arrangement in the WSM for a Panamax oil tanker Whole Ship Model (WSM).

Table 4.3, on the following page, shows the results of the study using the procedure that has been outlined. A propulsion coefficient of 0.7 was assumed for both ships with a carbon factor (tonnes of $CO_2$ emitted per tonne of HFO) of 3.1144 for HFO. The secondary effects on the ship have not been calculated, including the change in propulsion coefficient, generating thrust from the wind will reduce the loading on the propeller, and the side force due to the sails. This means that in Table 4.3 the total thrust from wind and the main engine combined is exactly the same for the baseline ship and the wing sail ship.

| Parameter | Units | Baseline ship | Wing sail ship |
|---|---|---|---|
| Operational speed | knots | 15 | 15 |
| Thrust provided by sails | kN | 0.0 | 262.8 |
| Thrust provided by propulsion engine | kN | 956.8 | 694.0 |
| Required propulsion engine power at 15 knots | kW | 10547.3 | 7650.6 |
| $CO_2$ emissions | tonnes per day | 135.6 | 98.4 |
| Fuel consumption | tonnes per day | 43.5 | 31.6 |
| Percentage change from baseline ship | % | 0.0 | -27.5 |

Table 4.3: A wing sail assisted Panamax oil tanker at a constant speed of 15 knots on a north Atlantic crossing compared with the baseline ship; the same ship without wing sails.

### 4.3.5 Costing considerations

*This subsection contains a description of relevant work carried out by members of the RCUK Energy funded research project "Low Carbon Shipping: A Systems Approach" (LCS) and is not the authors own work, although any summary or conclusive statements that follow this work are that of the author. A brief oveview of the LCS project from a ship design perspective is given in Appendix A.*

The costs were not examined in the initial feasibility study, but the final costs that were used for LCS were dependent on waterline length and ship type and are shown in Table 4.4.

| Ship type | Equation for Unit Purchase Cost (UPC) ($) |
|---|---|
| Container ship | $39.53 \times \text{Waterline Length}^2 + 17836 \times \text{Waterline Length} - 755225$ |
| Oil tanker | $191.55 \times \text{Waterline Length}^2 + 27048 \times \text{Waterline Length} - 3225000$ |
| Bulk carrier | $133.65 \times \text{Waterline Length}^2 + 3429 \times \text{Waterline Length} - 497297$ |
| LNG carrier | $191.55 \times \text{Waterline Length}^2 + 27048 \times \text{Waterline Length} - 3225000$ |

Table 4.4: Final UPC equations used for sails in LCS based on waterline length and ship type.

The Through-Life Cost (TLC) was assumed to be 8% of the Unit Purchase Cost (UPC) shown in Table 4.4. This Through-Life Cost (TLC) is for the maintenance associated with the sail only, the fuel consumption is caculated separately according to the engine use.

Accuracy of these costs could be improved by basing the cost on the calculated sail area. However the simpler study that was carried out for LCS did not calculate the sail area but directly calculated the change in thrust.

### 4.3.6 Further Considerations and Conclusions

Lift and drag data is hard to find and the flow around sails is complex. Interference between sails is also hard to specify.

Sail area could be trade-off between, structure, stability and cost. Unlike some other CRTs, where they either have an effect on the ship or are not used, for sails it is necessary to decide how much sails to use, especially because cost varies with the amount of installed sail area. It may be that due to interference between sails for larger and multiple sail installations the benefit to cost ratio may decrease.

Economics becomes much more important [Nijsten and de Vos, 2002] because journey times could vary. A slow ship is likely to benefit the most from wind propulsion as the apparent wind direction, $V_A$, will be relatively more from the stern than for a faster ship type [Nijsten and de Vos, 2002].

Although some big assumptions have been made, such as not accounting for the side force on the ship due to the sails, this study has shown that the $CO_2$ emission reduction potential of sail assisted propulsion is clearly large and difficult to quantify. Sails could benefit from examing the sensitivity of the sail performance to different assumptions and wind conditions in order to find the minimum and maximum possible $CO_2$ emission reduction. There may also be some benefit to a time domain model, although whether this could provide additional fidelity given the apparent uncertainties is unclear.

The ability to use sails may vary between ship size due to differences in upper deck layout. For instance, a container ship has very little space on deck. With wing sails there is scope to improve the design of future wing sails as the technology develops in order to delay boundary layer separation, increasing lift, and to reduce cost and weight [Bergeson and Greenwald, 1985].

The variation in propeller performance and engine and propeller matching are important because the thrust provided by the propeller at a given speed can vary considerably. The engine and propeller needs to work for a wide variation in thrust at the same speed this becomes more of an issue as the proportion of thrust that the sails are capable of providing increases.

## 4.4 Ship and CRT Modelling Observations

An appreciation of ship design and the ship impact is important when considering an alternative fuel. In the case of natural gas emissions and cost savings compared to oil are lower, when considering the ship impact, than comparing the specific fuel consumption of the two fuels independent of the ship [Calleya et al., 2011b]. The overall impact of selecting a fuel on a ship is shown in figure 4.10.

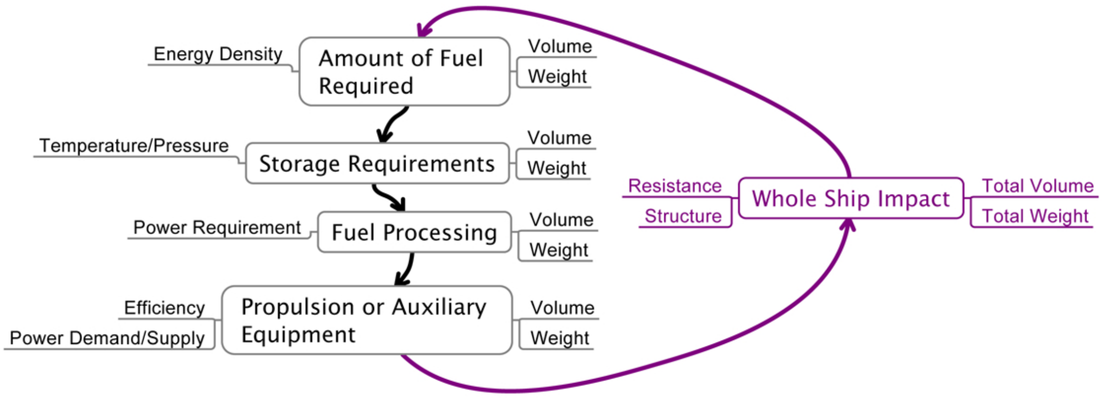



Figure 4.10: Potential changes to a ship design when changing to a different fuel [Calleya et al., 2011a].

Although some energy source (or fuel) changes, such as biofuel, require minimal changes to a ship design other energy sources (or fuels) require very large changes to a ship design, consider the changes to a ship needed for nuclear power. It is extremely unlikely that nuclear power could be retrofitted to an existing ship, especially considering the structural and stability requirements. Due to the additional considerations and potentially very large changes to the ship required for different energy sources different primary sources of energy are considered separately as primary energy source options in Table 3.2. Wind power is normally used in conjunction with a propeller as sail assisted propulsion and hence is treated as a CRT instead.

It is apparent that there is no clear, single cost-effective CRT that can easily be implemented as an alternative to oil-based fuels. This means that in the short-term multiple CRTs are likely to be adopted alongside an oil-based fuel infrastructure.

### 4.4.1 Design process for the selection of CRTs

The problem with using the design process shown in Figure 4.2 in the Whole Ship Model (WSM) is that the design process requires input from the designer in most stages to balance and manage the layout of a ship design whilst ensuring a suitable compromise is made between competing design objectives, such as maximising cargo whilst maintaining stability. It may also be necessary to perform this process many times to evaluate a wide range of ship and CRT combinations. Assuming that there are $36$ ship types, as shown in Table 4.1, with $20$ different CRTs ths need to be examined, including the baseline ship this amounts to $36 \times 21 = 756$ different ship and CRT combinations. This does not consider the use of multiple CRTs or varying design assumptions that will be examined in Chapter 7.

In order to automate the process and generate ship and CRT combinations quickly, it is necessary to make some simplifications to the design process shown in Figure 4.2. Figure 4.11 shows how the design process used in the WSM in Figure 4.2 was adapted to the design process used in Figure 5.2 in the Ship Impact Model (SIM).

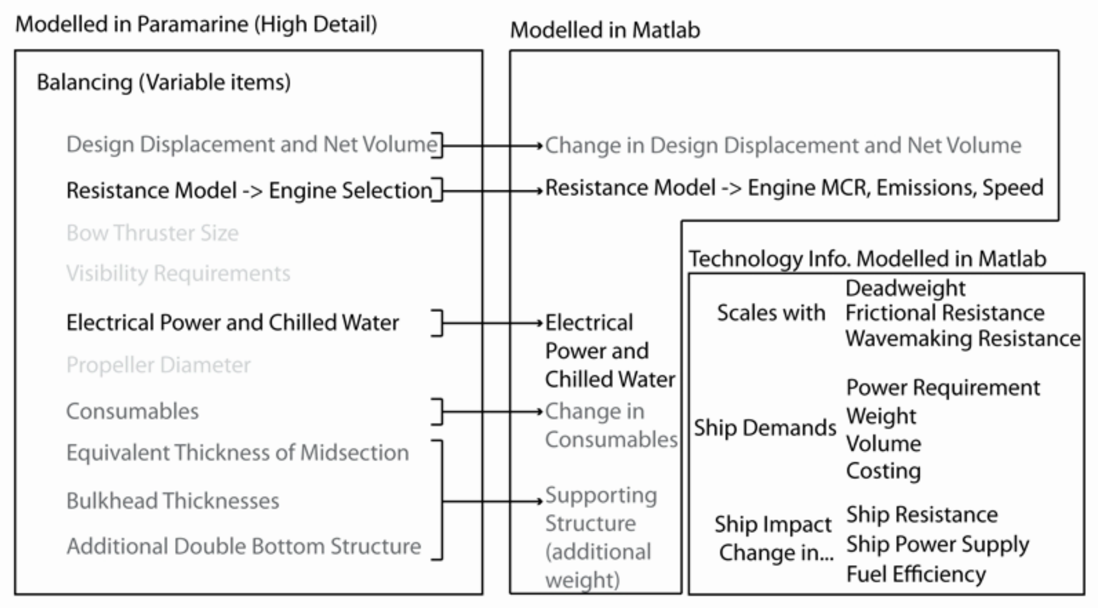



Figure 4.11: Design processes and data that can be modified in the Whole Ship Model (WSM) (left) to the Ship Impact Model (SIM) (right). There are also some examples (bottom-right) of how the effects on a ship due to a Carbon Dioxide Reducing Technologies (CRTs) can be scaled.

In Figure 4.11 design processes are represented according to how they are used when in the SIM:

- **Black** can be freely changed so they can be completely different in the SIM compared to the WSM.
- **Grey** can be changed relative to the baseline ship represented by a WSM.
- **Light grey** is set by the baseline ship represented by a WSM and can only be described indirectly (for example a change in propeller diameter could be described as a change in propulsion coefficient in a CRT file, this is discussed in Section 5.4).

This means that the WSMs only need to be used for the baseline ship (unmodified ship with no CRTs) and the ship impact of combinations of CRTs can be modelled using the SIM. Modelling small changes to a ship, such as those due to CRTs, rather than modelling the whole ship avoids repeating the whole design process, shown in Figure 4.2, each time. This is explained in more detail in the next Chapter in Section 5.1.

## 4.5 Summary and Conclusions

The studies on LNG and wind (in Section 4.2 and 4.3) allowed for a comparison between the two different design methods that were used, in the Whole Ship Model (WSM) and the Ship Impact Model (SIM), and assisted in understanding what aspects of ship and CRT combinations may need to be modelled in the WSM and what can be modelled in the SIM with a negligible change in the fidelity of the calculated $CO_2$ emission reduction and ship performance, compared to the WSM. In the next Chapter the development of the SIM will be discussed. The SIM allows for a more detailed analysis to be carried out, particularly due to the inclusion of secondary effects on the ship, such as the change in propeller efficiency due to sails.

There are many considerations when deciding what CRT should be used for a certain ship (or market) that may depend on the capability of the ship owner or operator as well as the region in which the ship is operating in. For example, ships operating in an ECA, where there are more stringent controls for $SO_x$ and $NO_x$ emissions may be more inclined to adopt natural gas as a fuel instead of investing in $SO_x$ and/or $NO_x$ emission reducing devices, such as using a Selective Catalytic Reduction (SCR), on an oil-based fuel engine.

Following the literature review and analysis of CRMs undertaken in Chapter 3 and in this Chapter the list of considerations concerning ship and CRM design and modelling presented in Section 2.8 can be expanded. Considering the necessity to reduce $CO_2$ emissions, mentioned in Section 2.3, the main considerations that have been observed so far for developing a model for ship and CRT combinations are:

1. Reducing cost is the main incentive to use CRMs.
2. Operational CRMs, operating speed profile and cleaning and maintenance, are important operational assumptions for CRTs.
3. There are qualitative barriers to selecting CRTs that could be based on opinion and/or risk.
4. Long-term solutions, particularly changes in fuel infrastructure, are important for larger reductions in $CO_2$ emissions by enabling the wider adoption of certain CRTs.

## Chapter 5

# Development of the Ship Impact Model

## 5.1 Development of a design process for Carbon Dioxide Reducing Technologies

Generally, most ships that carry cargo have an aft engine and machinery space and superstructure above this and holds along the length with ballast tanks around the cargo holds in varying forms (such as double bottom tanks, wing tanks, or hopper and topside tanks). The similarities between the midship section of the different cargo ship types is shown in Figure 5.1. The topological similarity of most ships within a given ship type allowed for the simplification of the modelling approach. The impact of the CRTs could be defined as only affecting certain parts of the ship, with other areas, such as crew accommodation, remaining unchanged.

The underlying basis for this model is the calculation of changes from a known baseline ship. Only the parts of a ship model that will change from a baseline ship due to a CRT need to be represented, allowing a much simpler and quicker iterative ship design spiral to be used to balance the design compared to a more conventional design spiral where the entirety of the design might be changed in each iteration [Watson, 1998].

Another assumption that permits a significant reduction on the computational time is to assume that any mass changes to the ship impact on cargo capacity. This is true for primary (directly from the CRTs) or secondary (such as changing the installed engine size due to having a lower power requirement) mass changes. This approach has also been adopted in the Life Cycle Performance Tool (LCPA) developed by the FP7 EC funded project (Breakthrough in European Ship and Shipbuilding Technologies (BESST) [BESST, 2013] where ship impact can be measured in terms of passenger cabins gained or lost. The alternative is to keep the cargo constant and vary the displacement, this requires an understanding of the variation in

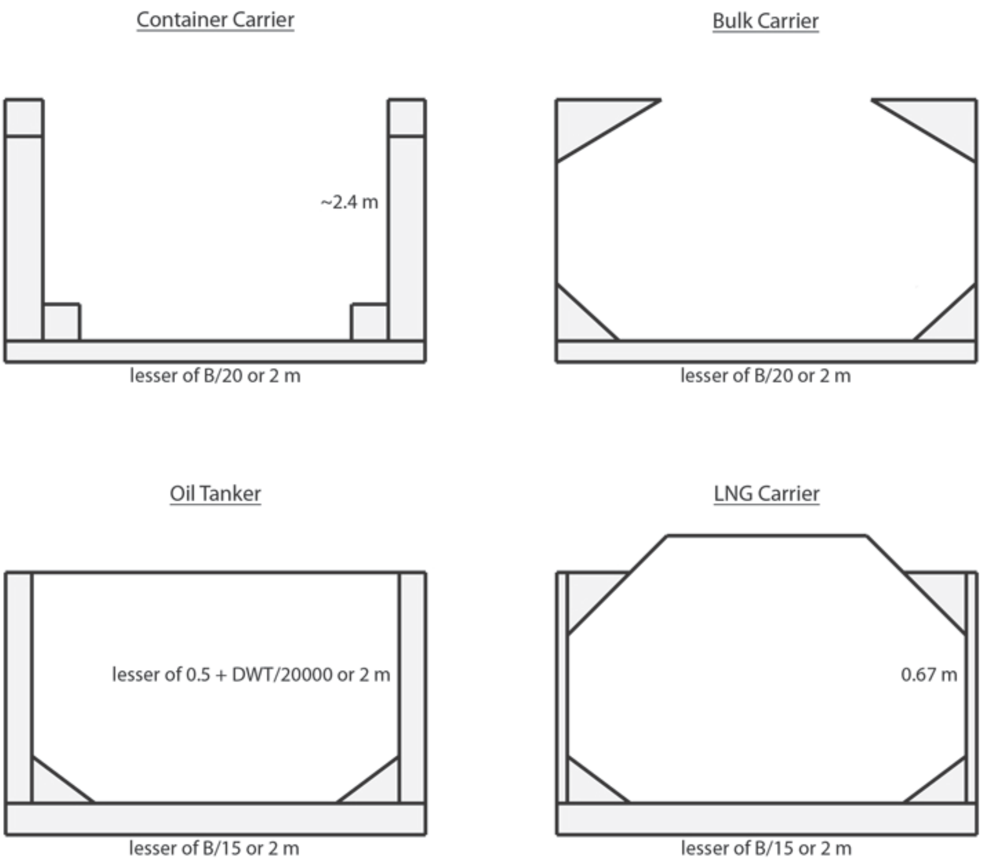



Figure 5.1: Similarity between Midship sections of different cargo ships.

resistance of the ship at different displacements, which requires an accurate three-dimensional representation of the hull form that could be computationally intensive, difficult to model accurately and requires an iterative process between the resistance model and changes in power and equipment due to changes in the size of the ship.

The Ship Impact Model (SIM) is divided into the following sections:

- Inputs and configuration of Inputs
- Selection of CRTs
- Ship Sizing (sizing of ship and CRTs based on design condition)
- Fuel/Energy usage and $CO_2$ emissions for different conditions
- Performance indices, including costing and profitability

Figure 5.2 shows a basic overall flow diagram of the SIM. The model is run initially for the baseline ship with no CRTs (no consideration of the architecture/technology interface).

After the baseline ship is examined the effect of an architecture/technology and/or each CRT combination on the baseline ship is examined.

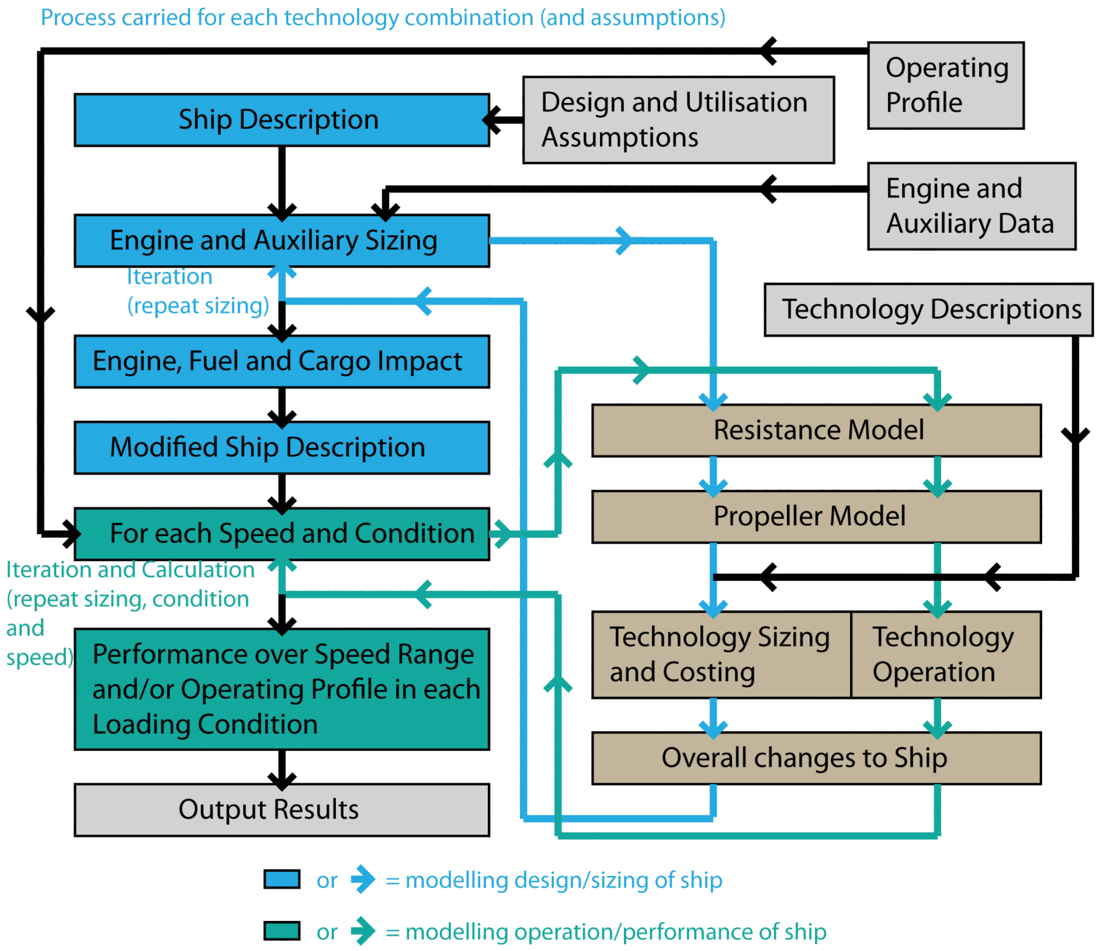



Figure 5.2: Ship Impact Model basic overall flow diagram

The primary and secondary changes are assumed to effect cargo capacity (as explained earlier) so that the displacement of the ship remains constant, the resulting change in cargo mass can be represented as in Equation 5.1:

$$\text{Cargo Mass}_{\text{modified}} = \underbrace{\text{Cargo Mass}_{\text{baseline}} - \text{CRT mass}}_{\text{Primary Effect}} + \underbrace{\text{Equipment mass}_{\text{baseline}} - \text{Equipment mass}_{\text{modified}}}_{\text{Secondary Effect}} \tag{5.1}$$

Secondary changes could be due to a change in engine power requirement due to a CRT such as waste heat recovery. This may mean that the installed power can be reduced (or on occasion increased) with a corresponding change in engine mass and potentially efficiency.

After each ship design is sized (for instance selecting adequate engines to meet the power requirement) the resistance, propeller and architecture/technology models are run again to calculate the performance of the ship over a range of operational speeds and loading conditions. For example, in the intial sizing the propeller is selected to provide the required thrust at the design speed and the same propeller is assumed at different operational speeds in order to calculate the operational efficiency of the propeller away from it's design point.

There is also a selector switch for retrofit and non-retrofit. For a retrofit it is assumed the main engine size cannot change for a non-retrofit all engines can be changed. Retrofit assumptions can be subjective and it is necessary to describe the effect of a retrofit in the function describing a particular CRT (CRTs can also be described as unsuitable for retrofit). How the CRT is described relative to the ship is described in more detail in Section 5.4.

### 5.1.1 Data sources

The raw input data for both the Whole Ship Model (WSM) (see Section 4.1) and the SIM came from a variety of sources. Ideally, especially when understanding how a ship is utilised at sea, sea trial data could be the most useful. However the amount of ship data available in the public domain is scarce.

Multiple data sources at different weight group levels, such as on an individual component level (weight group 2 or 3) or a whole ship level (weight group 1), were used to validate the SIM. For more information on the validation of the SIM see the proof of design, in Section 5.6.

Table 5.1 gives a summary of the data sources that were used, some of this data was used to generate the virtual WSMs in order to generate a valid ship description for the SIM.

| Data source (the most accurate data source is at the top) | Resistance | Volume | Mass |
|---|---|---|---|
| Sea trial and model test data | • | | |
| Manufacturers specifications | | • | • |
| General arrangements for specific ships | | • | |
| Generic hull forms | • | • | |
| Similar equipment (may not be specific to ships) | | • | • |
| UCL design data book | | • | • |
| Naval Architecture tools and approximations | • | • | • |
| Classification society and IMO guidelines | | • | • |

Table 5.1: Ship design data sources that were used and the type of information that they provide (with the most accurate at the top).

The hull forms, initially developed in 1997, that were used were a container ship and VLCC, these hull forms were generated to provide data for both interpretation of flow physics and Computational Fluid Dynamics (CFD) validation for a modern container ship with bulbous bow, no full-scale ship exists [MOERI, 2005].

The UCL ship design data [University College London, 2010] is mainly based on warships, rather than cargo ships, and was applied with careful consideration. Sometimes this entailed multiplying the UCL ship design data by a correction factor. For example, the space requirement per crew member can be much lower on a warship compared to a cargo ship, the latter having a much smaller crew in comparison to the amount of available crew space.

### 5.1.2 Inputs and support data

Due to the uncertainty in some of the assumptions in the SIM, such as the increase in resistance due to fouling, some of the assumptions are defined at the start of the program and can be readily modified. Assumptions specific to a CRTs are described in the file describing the CRT itself. See Section 5.4.

The support data, such as engine the engine database, allows secondary effects to be calculated automatically.

The full list of inputs to the Ship Impact Model are:

- Database of ship(s) to be selected (or modified).
- Database of CRT(s).
- Database of Supporting data (fuel list, engine List, auxiliary engine list, boilers and LNG tanks).
- Selection of ship and CRT to be examined and assumptions to use.

The process of selecting a ship includes the ability for the SIM to estimate the characteristics of a ship or group of ships from the database of ships based on a deadweight or displacement and a design speed.

## 5.2 Resistance and Powering

In the SIM there are three main functions to the resistance and powering calculation; the resistance model, the propeller model and the engine selection process. As shown in Figure 5.2, these functions form part of an iterative process.

### 5.2.1 Calculation of ship resistance

The resistance function uses the well-established Holtrop-Mennen regression formulae, for calculating the components of hull resistance and overall resistance [Holtrop and Mennen, 1982] with some updates from a follow on paper by Holtrop [Holtrop, 1984]. Section 5.6 explains more about how the resistance model was validated and calibrated to match better with model test data.

The resistance model uses inputs from the ships describing the hull form, such as wetted surface area and block coefficient. It is possible to describe the effects on wave-making resistance due to the bulbous bow and transom area of the particular ship that is being analysed. However the bulbous bow and transom area for each specific ship was not described for each individual ship for a few reasons:

- There is not enough available data to describe every ship. Fox example, lines plans, showing the shape of hull forms, are not widely available.
- Describing the bulbous bow area and position from a lines plan can be subjective and can add some uncertainty.
- Any unusual bow, transom or hull form shapes cannot be described in Holtrop-Mennen.
- It is difficult to check and compare results.

The bulbous bow and transom area cannot be ignored completely because their effect on wave-making resistance can be large, so the bulbous bow and transom area were sized according to the ratio of their dimensions to the beam and draught given in the example ship in the Holtrop-Mennen paper [Holtrop and Mennen, 1982]. Describing the shape and size of the bulbous bow and transom area relative to the beam and draught of the ship allows them to be approximately parametric. Some other variations in the bulbous bow size were explored in a sensitivity study for the bulbous bow, described in Subsection 5.6.1.

The resistance and propeller models are applied for both design and operational conditions. The operational condition also includes a fouling and weather allowance as a simple user defined increase in viscous resistance, this can be specified as a user input to the SIM.

#### 5.2.1.1 About regression formulae for calculating resistance

Though Holtrop-Mennen was developed in 1982 it is still widely used today [MARIN, 2010]. The big advantage of using regression formulae in the SIM is that the resistance for different speeds and loading conditions can be estimated extremely quickly, this is useful in the early design stages when it is necessary to quickly explore different design concepts.

An alternative to using regression methods is using Computational Fluid Dynamics (CFD). Model tests are still widely used alongside CFD [Bertram, 2000]. With CFD and without a physical model it can be difficult to ensure you are modelling flow correctly. Wave-making resistance and added resistance in waves are particular challenges for resistance models. CFD for wave resistance is an important commercial application [Bertram, 2000], it is also possible to miss characteristics of the flow from a regression method that is based on model testing or sea trials.

In the SIM regression formulae was used instead of CFD because the SIM has to examine many different ship designs and operational conditions extremely quickly, the resistance model is used many times.

### 5.2.2 Calculation of propeller performance parameters

The propeller model uses the Wageningen b-screw series [Oosterveld and Oossnan, 1975] of propellers and does not distinguish between retrofits, assuming that a new propeller is added after a retrofit. Similar to the resistance model, the propeller model cannot be used at very low speeds (below 2 knots).

Propeller design can be complex because it is a balance of many inputs to find the best propeller open water efficiency (EffO). The propeller function is run differently depending on if there is a gearbox or not and if the selected propeller is a Fixed Pitch Propeller (FPP) or a Controllable Pitch Propeller (CPP). The propeller diameter is fixed by the ship description (normally as large as possible) this reduces the number of unknowns and likely results in more efficient propellers. For the ship types and sizes that were selected for this analysis, see Appendix C, a two-stroke engine is normally connected directly to a FPP (with no gearbox). In this case the pitch over diameter ratio (P/D) is changed to meet the thrust requirement of the ship (ignoring efficiency) because the propeller speed is fixed by the engine speed. When a gearbox is used both the pitch over diameter ratio (P/D) and propeller speed (rpm) can be varied to meet the thrust requirement with the highest efficiency, designing the gearbox ratio accordingly.

The final part of the propeller function calculates the efficiency curve for the selected pitch over diameter ratio (P/D) and finds the propeller open water efficiency (EffO) that corresponds to the advance coefficient at the current ship and propeller speed. For a FPP as the pitch over diameter ratio (P/D) does not change the propeller open water efficiency curve is saved and re-loaded in each operational condition in order to calculate the propeller open water efficiency (EffO). If a CPP is used then in different operating conditions the pitch over diameter ratio (P/D) is changed to give a higher propeller open water efficiency (EffO) over a range of operating points. The CPP also uses the Wageningen b-screw series assuming that they have 98% of the efficiency of a Wageningen b-screw series FPP. This is because a CPP hub has to be bigger, compared to a FPP hub, to accommodate the mechanism for rotating the propeller blades, and the propeller blades themselves cannot overlap very much, which causes a slight reduction in the propeller open water efficiency (EffO).

### 5.2.3 Propeller and engine matching

Propeller torque is an additional output that can be used with engine power to select the engine and engine operating point using an engine map. This was not utilised for two reasons; due to not having a detailed engine map and this may be an unnecessary level of fidelity considering the propeller loading is assumed to be constant (this is also due to a lack of data). The engine map changes more considerably depending on how the engine is used, whether it is used in conjunction with a FPP, a CPP or for auxiliary power. Auxiliary power engines are normally used to produce AC electricity so their speed is constrained making them less efficient over part loads compared to a main engine that is used for propulsion power. So to mitigate the consequences of this the SIM has three engine lists for FPP, CPP and auxiliary power.

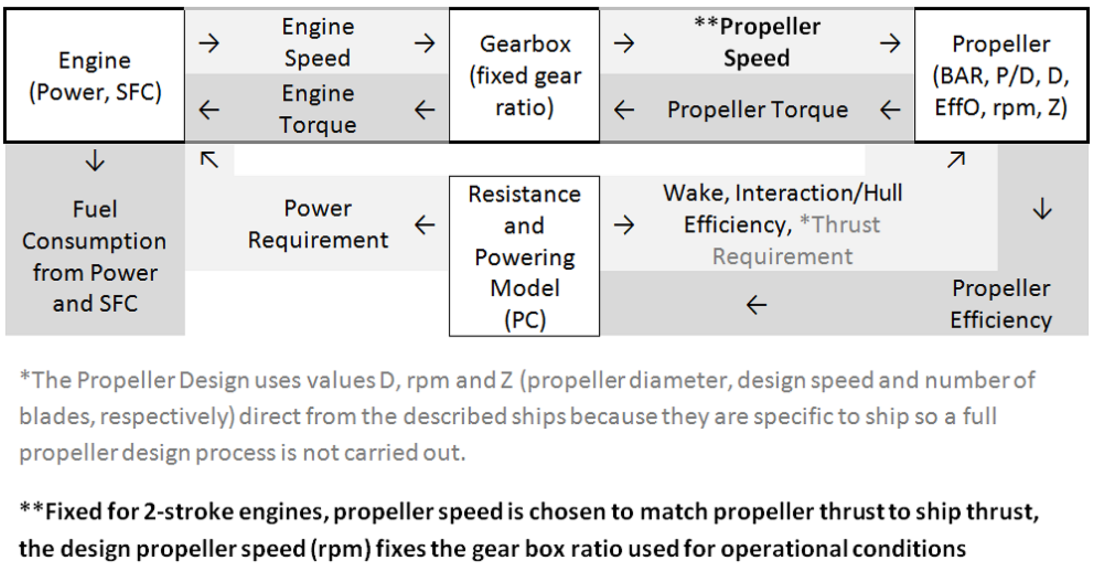



Figure 5.3: Interaction between the Propeller and Engine

The iterative relationship between the engine, propeller and resistance model is shown in Figure 5.3. The way the SIM has been written means that the thrust and powering requirements, outputs from the resistance and powering models, require the propeller open water efficiency to be calculated, while in order to calculate the propeller open water efficiency, the thrust and the power requirement (to calculate engine speed) are needed.

The main engine and auxiliary power engine data came from what data was publicly available from MAN [MAN, 2013] and Wärtsilä [Wärtsilä, 2013a] with a 5% correction from ISO standard tolerances (as the stated specific fuel consumption has to be within 5% engine manufacturers usually apply an optimistic reduction in specific fuel consumption equivalent to 5% [MAN, 2013] in their commercially available data). Engines for different fuels, such as LNG need to be separately defined. LNG engines and tanks are part of the main SIM and do not need to be separately described in a CRT description (See Section 5.4).

## 5.3 Ship Operating Profile and Utilisation Assumptions

### 5.3.1 AIS data from the Low Carbon Shipping project

*This subsection contains a description of relevant work carried out by members of the RCUK Energy funded research project "Low Carbon Shipping: A Systems Approach" (LCS) and is not the authors own work, although any summary or conclusive statements that follow this work are that of the author. A brief oveview of the LCS project from a ship design perspective is given in Appendix A.*

Coastal and satellite AIS data was collected by LCS, in 2012, for generating operational speed profiles. AIS position and itinerary data was copied from the website www.marinetraffic.com [MarineTraffic.com, 2013] for specific ships over a period of 2 to 3 weeks. After finding the AIS position inferred operational speed (distance/time) was unreliable, likely due to intermittent inaccuracies in position data, the AIS reported operational speed was used. Some vessels occasionally report very high AIS operational speeds, in these cases the operational speed value was replaced with the average of the preceding and following operational speeds.

The AIS position data was used to check if a vessel was in port by detecting if a vessel was stopped for long periods, although there are gaps in the data due to vessels going out of range of coastal AIS receivers. The operational speed profiles of five coastal ships were examined. Satellite AIS (from overhead satellites) is not limited by the position of coastal AIS receivers.

For both coastal and satellite AIS data, no change in the operational speed profile of a vessel was apparent due to the vessel being in ballast or in a loaded condition.

### 5.3.2 Determination of ship operational speed profiles

There is little published data on ship operating profiles. So operating profiles were developed with some expert judgement applied considering:

- Coastal and satellite AIS data.
- Limited published papers.
- Engine technical limitations.
- Weather.
- Fouling.
- Contracting and logistics.

The last three items are based on expert judgement. For example, it is likely that every ship spends at least a small proportion of time at 100% MCR. Fouling will also effect the operational speed at 100% MCR and in some cases heavy fouling may be an indication as to why a lot of ships appear to spend time just below the design speed, as the design speed may be achieved at around 75% MCR in sea trials and this may be around 100% MCR when the hull is heavily fouled.

It is also clear from guidance provided by engine manufacturers that some engines are spending extended periods of time at very low MCRs, guidance was given as this can be damaging to engines without careful attention from the operator [MAN, 2009].

The limited published papers from ship operators that were referred to were for oil tankers and container ships, by Teekay and Maersk, respectively [Armstrong, 2011] [Cerup-Simonsen et al., 2009] [Jakobsen, 2009]. All the data looked at was from 2009 to 2012, this is important because after the 2008-2009 economic downturn ship operators slowed ships down [Armstrong, 2011].

It was necessary to make comparisons between the data for different ship types in order to ensure that trends in the data were captured, for instance both oil tankers and LNG carriers appear to spend more time close to the design speed when compared with bulk carriers and container ships. It was not possible to use a single reference for each operating profile because the accuracy of one reference over another is not clear and we are interested in a typical operating profile rather than one that could be specific.

The operating profile is based on operational speed rather than engine power (as a percentage of MCR) as an operating profile based on MCR would cause some CRTs to have no effect on fuel consumption if the same engine operating power is maintained, but rather would cause a change in operational speed instead.

Once the initial operational speed profile has been calculated for the baseline ship (with no CRTs) the same operational speed profile is then demanded for each ship and CRT combination. Some specific ship and CRT combinatons may not be able to achieve the demanded operational speed profile (for example, when the ship is heavily fouled). Setting the initial operating profile relative to design speed and MCR allows ships with different design speeds to use a similar operational speed profile.

Table 5.2 shows the operating profiles that were described for each ship type, the activity column, helps to add some expert judgement into how the operating profiles were conceived.

| Activity | Speed calculation | Bulk carriers | Container ships | Oil tankers | LNG tankers |
|---|---|---|---|---|---|
| Low speed | $0.3\times$Design speed$+0.5$ | 2% | 3% | 3% | 3% |
| (manoeuvring) | $0.4\times$Design speed | 1% | 3% | 2% | 1% |
| Slow steaming | Speed at 25% MCR | 4% | 25% | 1% | 4% |
| | Speed at 37.5% MCR | 23% | 43% | 3% | 7% |
| Contracted speed | Design speed$-3$ knots | 46% | 18% | 24% | 29% |
| (cruising speed) | Design speed$-1.5$ knots | 16% | 7% | 63% | 53% |
| Full speed (bad weather) | Speed at 100% MCR | 8% | 1% | 4% | 3% |

Table 5.2: The proportion of time spent at each speed for each ship type.

There are some improvements that could be made to the operating profiles presented in Table 5.2 if there was more data available:

- In order to generate a generic operating profile data is needed from different markets and years.
- The same operating profiles, in terms of operational speed were used for loaded and ballast. In some markets it may be the case that the ballast legs are carried out quicker in order to take on the next cargo quicker.
- Operating profile could also be linked to auxiliary power usage as well as be a function of ship size.

Not capturing the ship size in the described operating profiles has the biggest effect on container ships due to the large variation in $CO_2$ emissions with ship speed. Smaller coastal container ships can have a design speed between 18 and 20 knots, while larger ocean going container ships can have design speeds between 23 and 25 knots. Crew related decisions are also not being captured. Crew behaviour could include a change in the operating profile of a vessel to meet schedules or maintaining engine power (rather than operatonal speed) in different ship conditions (such as after retrofitting different CRTs or when carrying ballast).

### 5.3.3 On-board measurements of auxiliary power

On-board measurements of two coastal ships have given some indication that auxiliary power can be treated as constant for each operating condition the ship is in. Small fluctuations in load were of 100-200kW and around 100kW while at sea, for a 166.3 metre long RoPax Ferry and a 137.5 metre long 822 TEU container ship, respectively [Kaehler, 2004] [Kaehler and Jaoual, 2004]. From the container ship on-board measurements it was found that electrical consumers related to manoeuvring and deck equipment caused the biggest fluctuations in load, with the bow thruster causing an average total electrical load of around 500kW while manoeuvring to sharply increase to a maximum around 1000kW for a minute then back to 500kW [Kaehler and Jaoual, 2004]. The container ship did not transport many reefer containers during the voyage, so the load fluctuations that could be caused by reefer containers is not known [Kaehler and Jaoual, 2004].

A power balance for a 45 000 tonne cargo ship, shown in table 5.3, also illustrates a large load change caused by the bow thruster and the changing of generators to meet demand.

| Item | Seagoing | Seagoing with reefer containers | Manoeuvring with thruster | Cargo handling | In port |
|---|---|---|---|---|---|
| Load | 539 kW | 645 kW | 2820 kW | 1157 kW | 395 kW |
| Running generators | 720 kW | 720 kW | 3320 kW | 2600 kW | 720 kW |
| Running generators / Load | 74.8% | 89.6% | 84.9% | 44.5% | 54.9% |
| Installed 3320 kW / Load | 16.2% | 19.4% | 84.9% | 34.9% | 11.9% |

Table 5.3: Total power balance for 45 000 tonne cargo ship with 3320 kW of generators [Rødseth and Mo, 2010].

### 5.3.4 Auxiliary power assumptions

For cargo ships the propulsion engine power is still the biggest source of $CO_2$ emissions compared to the auxiliary power engine. This is illustrated in figure 5.4, in this case the differences between the distribution of energy for oil and LNG are due to the change in efficiency of the propulsion power engine relative to the auxiliary power engines.

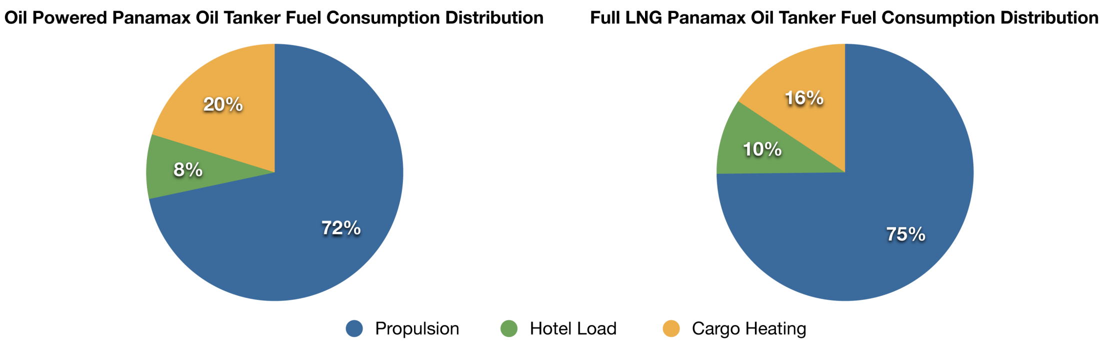



Figure 5.4: Distribution of fuel consumption for an oil (left) and LNG (right) powered Panamax oil tanker [Calleya et al., 2011b]. This study is discussed in Section 4.2.

There was not enough energy usage data available from on-board measurements of auxiliary power utilisation (including the hotel and cargo energy requirements) to produce a realistic generic power usage profile for each ship type. So the auxiliary power usage was kept constant in all conditions and at all operational speeds, although different operating procedures, such as manoeuvring and cargo handling (including running cargo pumps), may have higher energy demands on the ship. Based on the limited data presented and discussed in Subsection 5.3.3 the auxiliary power utilisations shown in Table 5.4 were used.

| Item | Bulk carriers | Container carriers | Oil tankers | LNG tankers |
|---|---|---|---|---|
| Auxiliary power utilisation at sea | 40% | 23% | 40% | 32% |
| Heat energy utilisation at sea | 69% | 69% | 69% | 34% |
| Auxiliary power utilisation in port | 28% | 16% | 28% | 23% |
| Heat energy utilisation in port | 69% | 69% | 69% | 34% |

Table 5.4: Assumed auxiliary power relative to the installed power for each ship type.

Representing the auxiliary power usage relative to the installed power can be misleading and will not work for unconventional ships however it allows for installed power to be used as an input from the ship, which is normally easily available information and allows for scaling approximately for different ship sizes.

The heat energy (normally provided by a boiler), shown in Table 5.4, is treated separately because changing the types of energy between heat energy and electrical energy will always incur energy losses. In order to calculate the cargo heating boiler size a simple analysis of oil tanker cargo heating boiler sizes was carried out to come up with a approximate relationship between deadweight and installed heating capacity. This was based on a series of ships by a Croatian shipbuilder and the stated boiler fuel consumption of a container ship [Croation Shipbuilding, ] [Grieg Star, 2012]. Some ships also have a composite boiler that uses waste heat from the main engine, this could use the lower temperature heat that would not be utilised by a conventional waste heat recovery system.

### 5.3.5 Summary

A steady-state and expert judgement, considering safety, capability and capacity considerations, has been used to estimate on-board energy consumption due to only having a small amount of data available for specific ships. This can be justified in most situations mainly because:

- Single large consumers, such as bow thruster or reefer containers, can be used to set the installed power.
- Auxiliary power load is fairly constant with small fluctuations.
- Operational procedure and crew behaviour can be highly uncertain, for instance the crew may be overly cautious in order to avoid black-outs and have little incentive to save fuel [Macneil, 2012].

## 5.4 Technology (CRT) Descriptions and Interface with the Ship Description

The technologies themselves are described as changes in up to 19 characteristics of the baseline ship. The changes to the baseline ship can be described in three categories, for different types of effect on the ship. The effects on the ship and how they are recorded are listed in Table 5.5.

The interface between the CRTs and the ship must be flexible enough to deal with different technology architectures. To aid in the development of the interface, a reduced set of CRTs was used to provide examples of the interface parameters that are required. The list in Table 5.5 was found to work well as an interface between the potential different CRT and ship combinations that could be considered. Most individual CRTs can be described by as few as three or four parameters from Table 5.5. The development of the list in Table 5.5 was a collaborative process involving the SIM model designer and the subject matter experts (for specific CRTs) to ensure the correct information is available from the ship and the ship represents the CRTs in the correct way.

The CRT files (implemented as MATLAB functions) can access the information from the ship shown in Table 5.6, so that the outputs described in Table 5.5 can be functions of the information in Table 5.6. A CRT file could be as simple as an engine improvement that reduces the specific fuel consumption by X%, this would not require any reference to the inputs, described in Table 5.6, or a CRT file can also be a much more complex function of the inputs. Although a detailed

| Type of Parameter | Parameter | Units |
|---|---|---|
| Resistance | Change in Viscous Resistance | $\pm$ % |
| Parameters | Change in Wetted Surface Area | $\pm$ $m^2$ |
| | Change in Propulsive Coefficient | $\pm$ % |
| | Change in Overall Resistance | $\pm$ kN |
| Engine and Fuel | Change in Main Engine Specific Fuel Consumption | $\pm$ % |
| Parameters | Change in Auxiliary Engine Specific Fuel Consumption | $\pm$ % |
| | Change in Engine Shaft Speed | $\pm$ % |
| | Main Engine Fuel Selector | |
| | Auxiliary Engine Fuel Selector | |
| | Heat Boiler Fuel Selector | |
| Service | Change in Main Engine Power | $\pm$ kW |
| Parameters | Change in Main Engine Power | $\pm$ kW |
| | Change in Auxiliary Engine Power | $\pm$ kW |
| | Change in Shaft Generator Power | $\pm$ kW |
| | Change in Heat Energy | $\pm$ kW |
| | Deck Space Impact | $\pm$ $m^2$ |
| | Change in mass due to CRT (Cargo Impact) | $\pm$ te |
| | Can technology be retrofitted? | Yes/No |
| Cost | Unit Purchase Cost of CRT | $\pm$ \$ |
| Parameters | Through-Life Cost of CRT | $\pm$ \$ |

Table 5.5: Inputs from Carbon Dioxide Reducing Technologies (CRTs) to ship.

customisable model could be described in a CRT file, this was only done in one instance. In most cases it was found to be more effective to look at a complex CRT, such as a waste heat recovery system, by pre-calculating a look-up table of different operational conditions that can be referred to by the SIM. The look-up table can be generated by the CRT file itself on the first iteration of the model or it can be generated in different software entirely. This had the advantages that it was possible to interface with a specialist software package, the engine simulation software GT-Power was used in the ETI HDVE project (the ETI HDVE project is explained in Appendix B), and the run-time could be decreased by having pre-calculated look-up tables.

Consider a simple example of a waste heat recovery system, where the output power is related to

| Type of Parameter | Parameter | Units |
|---|---|---|
| Utilisation Parameters | Operating Speed | knots |
| (for particular speed and | Demanded Main Engine Power | kW |
| condition) | Demanded Auxiliary Engine Power | kW |
| | Demanded Heat Power (could be boiler power) | kW |
| | Demanded Propeller Torque | kNm |
| | Demanded Retrofit | Yes/No |
| Design Parameters | Design Speed | knots |
| (set by design condition) | Installed Main Engine Power | kW |
| | Installed Auxiliary Engine Power | kW |
| | Installed Shaft Generator Power | kW |
| Ship Chacteristics | Cargo Density | te/m$^3$ |
| (51 variables - taken directly | Available Deck Space | m$^2$ |
| from the full ship description) | Waterline Length | m |
| | Beam | m |
| | Wetted Surface Area | m$^2$ |
| | etc... | |

Table 5.6: Outputs from ship to Carbon Dioxide Reducing Technologies (CRTs).

the total power of its host engine. A waste heat recovery system could be described by Equation 5.2:

$$\text{Power}_{\text{Waste Heat}} \propto \frac{\text{Output Power}_{\text{Host Engine}}}{\text{Rated Power}_{\text{Host Engine}}} \tag{5.2}$$

There is also a choice as to whether the $\text{Power}_{\text{Waste Heat}}$ is used for main propulsion power or hotel/auxiliary power. The waste heat recovery function is referred to each time the model looks at a different condition or ship speed.

The CRT can also be sized directly from the input ship specification, which will not change between different ship operating conditions. For example, a Mewis duct, improving flow into the propeller, could be sized by referring to the propeller diameter in the ship specification (the performance of a duct is likely to be a function of the operational speed of the ship). If a required variable does not exist, particularly variables that relate to stability or structure, that may not included due to the simplification of the design process in the SIM, then a separate WSM can be used to find a proxy variable, such as a relationship between GM, length, beam and/or ship type.

Having fuels treated as a separate option allows easier estimating of costs. The fuel selection associated with a CRT file could also be used to isolate fuel incompatibilities that may occur when combining some CRTs.

In the SIM the CRTs are implemented by describing changes to a baseline ship, so that if the CRT interface is left blank the baseline ship will be calculated. This has the advange that only the aspects of the ship that change due a CRT need to be described. However for detailed changes to the ship, this interface can be harder to use especially for parameters that are described as relative changes to the baseline ship, as shown in Table 5.5. By examing a variety of different CRTs it was decided whether changes should be relative or absolute. For example, an absolute overall resistance is needed to include the calculated the thrust from sails. Changing the engine list used by the model could be one alternative way to implement engine changes instead of using the CRT interface described in Table 5.5.

## 5.5 Output Format and Utilisation of the Ship Impact Model (SIM)

The SIM has had two main objectives; to advise, as part of the LCS project [Calleya et al., 2012] [Smith et al., 2010], on what carbon dioxide emission reductions are possible for shipping and how best to regulate shipping to achieve this; and to act as an early stage design tool, as part of the ETI HDVE project (the ETI HDVE project is explained in Appendix B), to select which technologies to develop further.

The outputs from the SIM are saved to a spreadsheet in the format depicted in Figure 5.5. This output format was developed to allow post processing of the SIM outputs to provide a simplified description of the ship impacts of CRTs that could be used in a model of the wider shipping system, used in LCS, without requiring run-time execution of the SIM to generate each of thousands of ships in the global fleet. This is described in Calleya et al [Calleya et al., 2012]. The output structure also allows subject matter experts to assess the performance and impact of their technology on the ship, at a high level.

## 5.6 Ship Impact Model Proof of Design

A model test report for a chemical tanker was made available from Marintek [Nervik, 2000] in the ETI HDVE project (the ETI HDVE project is explained in Appendix B). Although this ship

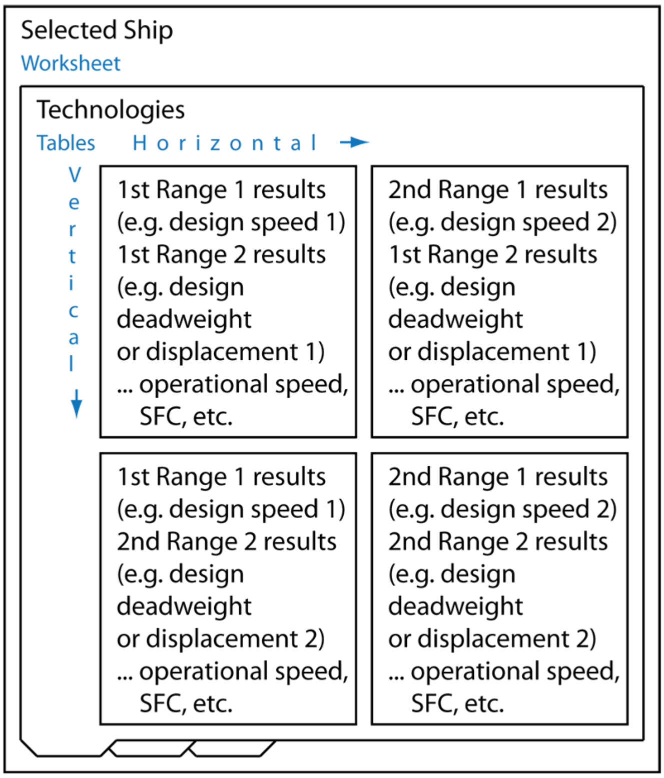



Figure 5.5: Format of output spreadsheet.

is smaller than the ships selected in this work and in LCS it does provide a much needed point to validate the detailed calculations in the resistance and powering model in the SIM, discussed in Section 5.2. The chemical tanker is 135.7m long has a design speed of 15 knots with a design displacement and a design deadweight capacity of 19363 tonnes and 15800 tonnes, respectively. Model tests, represent specific ships rather than approximating a range of ships (as regession methods do) and will also have errors associated with them, but for specific designs model tests are generally more accurate than regression methods [Bertram, 2000].

As mentioned in Sub-subsection 5.2.1.1, the advantage of using regression formulae is that they allow for the resistance for different speeds and loading conditions to be estimated extremely quickly. There are different regression formulae, assumptions and corrections that could be formulated and used for resistance and other components of the model in order to better approximate the performance of the range of ships considered.

It was found that two iterations works well for the baseline ships, as convergence is quick, and more iterations do not give any more useful detail, however more iterations should not be ruled out, especially when examing CRTs that have a large effect on the propulsion coefficient or resistance. The iterative sizing processes are shown by the coloured lines in Figure 5.2.

The skin-friction resistance is a straight forward calculation based upon the widely used and adopted ITTC 1957 Model-Ship Correlation Line. By comparing the method for calculating resistance established by Holtrop-Mennen 1982 [Holtrop and Mennen, 1982] to the model test data it was found that at higher Froude numbers, around 0.5-0.6, (relevant to shorter and faster ships) Holtrop-Mennen 1982 [Holtrop and Mennen, 1982] was overestimating wave-making resistance. This was found to be a documented issue [Holtrop, 1984]. A different regression formulae was used for higher Froude numbers with the existing formulae used for lower Froude numbers with an interpolation between the two methods in between. As suggested by the 1984 Holtrop update paper [Holtrop, 1984].

### 5.6.1 Bulbous bow

A bulbous bow relates to the creation of a bow wave and primarily effects wave-making resistance. Figure 5.6 shows a quick study looking at varying the area of the bulbous bow in the resistance model. A bulbous bow was included in the resistance model because most ships that were being examined have a bulbous bow (see Appendix C) and the reduction in resistance of the bulbous bow at higher Froude numbers was found to be quite large, as shown in Figure 5.6. However, estimating the bulbous bow size of different ships in terms of area and height proved difficult and not entirely accurate so instead the bulbous bow was chosen to be dimensionally similar to an example given in the Holtrop-Mennen 1982 paper [Holtrop and Mennen, 1982] rather than guessing. There are also a few additional parameters that describe ship shape, that were ignored for similar reasons to the bulbous bow, they are unlikely to provide any extra fidelity.

Figure 5.6 shows the effect on resistance of varying the bulbous bow size on a chemical tanker with a design speed of 15 knots (for which there was a resistance estimate based on model test data that could used to validate the model). At lower Froude numbers, where skin-friction is a bigger proportion of overall resistance, the size of the bulbous bow does not matter as much. At the design speed, 15 knots, the size of the bulbous bow could cause the resistance to change by as much as 12%. The effect on the majority of the large cargo ship types that are the focus of this work will be effected less than this by the bulbous bow because these are larger ships with lower froude numbers compared to the chemical tanker that has been used here for validation. The bulbous bow will have the biggest effect on the resistance of the container ships, as container ships operate at higher speeds and hence Froude numbers compared to the other ship types.

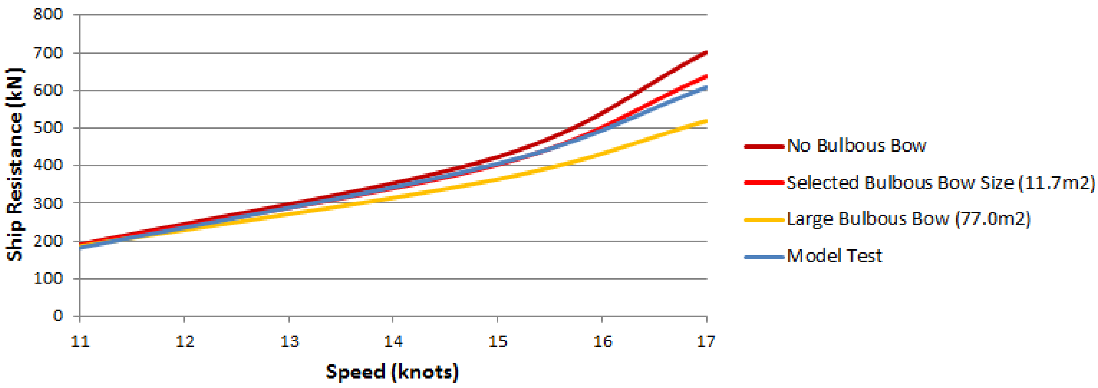



Figure 5.6: Affect of bulbous bow size on overall resistance for a 135.7m long chemical tanker with a design speed of 15 knots (using Holtrop and Mennen, 1982).

The model test data line shown in Figure 5.6 is the full-scale ship performance from the model test data that was made available from Marintek (this includes any correction factors required from model experiments carried out by Marintek) [Nervik, 2000]. This was compared to the resistance characteristics of the same ship with different bulbous bow sizes that were calculated out using Holtrop and Mennen, 1982. Initially this was done quickly by applying a correction factor that is a multiplication of the wave-making resistance and correlation allowance to replicate different size bulbous bows then the areas of different bulbous bow sizes were calculated.

### 5.6.2 Hull efficiency elements

The chemical tanker model test data also provided enough detail to allow comparison between the hull efficiency elements, which are shown in Table 5.7.

| Parameter | Ship Impact Model | Model test | Separate UCL model |
|---|---|---|---|
| Relative rotative efficiency | 1.016 | 1.009 (varies between 1.007 and 1.012) | - |
| Thrust reduction coefficient | 0.196 | 0.236 (varies between 0.214 and 0.248) | 0.197 |
| Wake factor | 0.342 | 0.376 (varies between 0.370 and 0.385) | 0.327 |
| Blade area ratio (corrected) | 0.519 | 0.515 (constant) | - |

Table 5.7: Comparison of hull efficiency elements calculated in the SIM, model test and another separate resistance and powering model at UCL.

The blade area ratio was estimated from Keller's formula [Holtrop and Mennen, 1982], which calculates a minimum blade area ratio to avoid cavitation. In practice blade area ratio is another estimate in the propeller model, however in order to reduce the unknowns in the propeller model and allow for automation blade area ratio was assumed to be related to Kellers formula. During the ETI HDVE project (the ETI HDVE project is explained in Appendix B) a correction factor to Keller's formula was found by looking at a few ships in order to give similar blade area ratios to existing ships. This was found to be 1.14 for single screw and 1.16 for twin screw ships.

The thrust deduction coefficient, t, and the wake factor, w, proved the most difficult to estimate; depending on what CRTs are of interest a better estimate may be required if this data is available.

### 5.6.3 Propeller

As mentioned in Section 5.2.2, the propeller model is complex. The propeller diameter is fixed by the ship description (normally as large as possible) and is sized to fit the ship by changing the propeller pitch over diameter ratio (P/D) to match the required thrust of the ship. In the sizing process the advance coefficient (J) is multiplied by a design factor of 1.25. This was determined by comparing the calculated propeller efficiencies to a limited amount of model test data and ensuring that there is no decrease in propeller open water efficiency (EffO), after the peak open water efficiency is reached there is a steep decrease in the propeller open water efficiency (EffO) at higher advance coefficients (J), at higher advance coefficients (likely corresponding to higher ship speeds). This means that the model chooses a slightly higher and pessimistic pitch over diameter ratio (P/D) in the design process. Then for a Fixed Pitch Propeller (FPP) the operational performance, including the propeller open water efficiency (EffO), is calculated based on the selected pitch over diameter ratio (P/D) (not using the design factor of 1.25).

The propeller model was also cross-checked with an Microsoft Excel based propeller model based at UCL, which gave the same results.

### 5.6.4 Design Cargo Capacity (Deadweight)

Having every CRT impact on cargo could reduce the accuracy of a CRTs performance calculation as cargo ships are not always full to capacity (particularly for container ships and when in ballast for other ship types). In order to mitigate this assumption, particularly allowing for the economic impact of a CRT to be accurately calculated , the operational design condition cargo capacity and operational ballast condition cargo capacity from the input ship are described separately from design capacity and are used for calculating operational performance. In the design process the design and ballast cargo capacity (deadweight) is used, however when at sea ships are not always full so the operational design condition cargo capacity and operational ballast condition can be used to reflect this. For example, if a CRT has a large impact on the cargo capacity of a ship but the ship has an operational design cargo capacity that is half of the design cargo capacity (the ship is half full) then a CRT will have no effect on the amount of cargo that can be carried because it can fill the empty cargo capacity. This is a particular problem for container ships that are rarely full to their design capacity.

### 5.6.5 Summary and Conclusions

When comparing the SIM to model test results it was found that the skin-friction component of resistance and the relative rotative efficiency can be approximated well. The wave-making (or residuary) resistance component of resistance is difficult to estimate. Wake factor can be approximated satisfactorily and thrust deduction was the least accurate. These conclusions are only based on one comparison because very limited data was available.

The Ship Impact Model (SIM) is sufficient as a concept tool and gives results that are appropriately accurate when placed in the use context of:

- The time taken to run the model in order to quickly compare architecture/technology options (approximately 30 seconds for a simple architecture/technology and ship combination) - a CFD model would likely take longer to run.
- Accurate enough to select one architecture/technology option over another.
- Flexibility to look at different ships and architecture/technology combinations. CFD or model testing tends to be more limited to the specific ship that is being examined.
- Inexpensive, when compared to CFD simulations and model testing, which are likely to cost more in time and money to carry out.

With early ship powering and resistance estimation it is normal that errors of approximately around 5% or more may be possible. There is always more that can be done and regression models and CFD both have their limitations when predicting real world performance, hence the need for model tests and sea trials. There is also very little data available to check against real world performance. Using a simple potential flow code it may be possible to get a better estimate of wave resistance and hull efficiency factors, whilst still carrying out calculations quickly. Combining regression formulae and CFD would give additional certainty of the results. However, the existing model is accurate enough as a concept design tool.

## 5.7 Designing Ships for an Operational Speed Profile

The SIM can be used to design a ship and CRT combination to have low $CO_2$ emissions over an operating profile by independently setting:

- Hull form design speed.
- Engine and propeller design speed.
- Maximum speed.

In this way the overall ship can be made to be more flexible, however more flexible systems usually come at a loss in efficiency at a single point. It is possible that a more flexible ship that has lower $CO_2$ emissions could have a worse EEDI, this is demonstrated by the SIM results shown in Table 5.8. A comparison was carried out with a Panamax container ship and a VLCC (Very Large Crude Carrier) by carrying out the process used on current ships where the hull form, engine and propeller are all designed to the same design speed and comparing this to the same ship with a different hull from the ship database that is blockier, allowing for additional cargo, designed for a speed that is 5 knots lower than the design speed. For example, this means that for the 25 knot container ship, a 20 knot ship of the same capacity was used with a larger engine installed to reach a speed of 25 knots; both ships used exactly the same operating speed profile.

In Table 5.8, the Panamax container ship with a 20 knot hull form is worse than the conventionally designed ship, with a 25 knot hull form, in terms of the ratio of mass of $CO_2$ emissions to cargo over an operating profile and also worse in terms of the EEDI, this is due the hull form being less efficient at the design speed.

However, the VLCC with a 10 knot hull form, represented in **bold** in Table 5.8, is better over an operating profile than the conventionally designed ship, with a 15 knot hull form, in

| Ship type | Ship design speed | Hull form design speed | $CO_2$ emissions (te/day) over operating profile | ratio of mass of $CO_2$ emissions to cargo over operating profile | EEOI (daily) | EEDI |
|---|---|---|---|---|---|---|
| Panamax | 25 | 20 | 290 | 0.0079 | $2.6e^{-5}$ | 45.2 |
| container ships | 25 | 25 | 244 | 0.0070 | $2.3e^{-5}$ | 42.7 |
| Very Large Crude | **15** | **10** | **528** | **0.0019** | **$1.0e^{-5}$** | **3.9** |
| Carriers (VLCC) | 15 | 15 | 497 | 0.0021 | $1.1e^{-5}$ | 3.3 |

Table 5.8: Performance comparison over an operating profile between a conventionally designed ship and one designed with a hull form that is 5 knots slower, blockier, allowing for more cargo to be carried.

terms of both the ratio of mass of $CO_2$ emissions to cargo over an operating profile and the EEOI (daily). However the EEDI and the calculated $CO_2$ emissions of the ship are worse than the conventionally designed ship because the EEDI and the calculated $CO_2$ emissions do not consider the operating profile and cargo, respectively.

## 5.8 Summary and Conclusions

Some assumptions in the SIM contain a lot of uncertainty, particularly those relating to operation, such as the operational profile, auxiliary power utilisation (e.g. power requirement for refrigerated and chilled containers), displacement and cargo load when the ship is in operation (this is likely to vary between voyages).

Finding as much detailed accurate performance data for validating ship models is important, particularly from sea trials. In most cases a very limited amount of data is available, this could be due to:

- Manufacturers of CRTs often quote best cases [Hochkirch and Volker, 2010] and the quoted fuel consumption for ship charterers can also be inaccurate.
- Ship owners and operators do not want to share potentially commercially sensitive fuel consumption.

- Ship owners and operators can only collect a limited amount of data due to commercial incentives (sea trials are limited).

- Ship owners and operators may not understand what and how data needs to be recorded. Some data has to be recorded simultaneously; for example, collecting shaft torsion and ship speed data simultaneously could be used to estimate the level of fouling and added resistance due to waves.

Ship data can be disseminated by keeping the name of the ship anonymous, as there is often no need to publish the name of the ship or even the original data that a calculation may of been based upon. In some cases, particularly with operational CRMs, changes in fuel consumption due to CRMs, such as trim optimisation or weather routing can be measured onboard and reduced by trial and error. Computer based models, such as the SIM, can provide an initial estimate of what ship configuration could be required for the lowest $CO_2$ emissions or the lowest cost. Feedback from ship trials and operation will help to develop computer based models, such as the SIM.

Comparing the baseline ship to the same ship that has been modified by the addition of CRTs can reduce the effect of inaccuracies in the original baseline ship model. The accuracy of the modelling would then depend on how accurately the ship responds to changes.

Considering the necessity to reduce $CO_2$ emissions, mentioned in Section 2.3 (and expanding on the Chapter summaries in Section 2.8 and Section 4.5), the main considerations that have been observed so far for developing a model for ship and CRT combinations are:

1. Reducing cost is the main incentive to use CRMs.

2. Operational CRMs, operating speed profile and cleaning and maintenance, are important operational assumptions for CRTs.

3. There are qualitative barriers to selecting CRTs that could be based on opinion and/or risk.

4. Long-term solutions, particularly changes in fuel infrastructure, are important for larger reductions in $CO_2$ emissions by enabling the wider adoption of certain CRTs.

5. Operational feedback and detailed dissemination of detailed design data is important to improve modelling and validation (data for validating models is limited, as discussed in this Section).

# Chapter 6

# Initial Results and Further Development of the Ship Impact Model

## 6.1 Introduction to Results presented in Chapters 6 and 7

The last three chapters have examined different aspects of modelling ships and Carbon Dioxide Reducing Technologies (CRTs) from a CRT biased perspective to a ship model perspective:

- Chapter 3 reviewed and selected CRTs.
- Chapter 4 examined two CRTs in detail and how they interact with a ship model.
- Chapter 5 detailed the development a ship model to incorporate CRTs.

In Chapter 3 a list of CRTs with a high potential of reducing $CO_2$ emissionsl, represented in Table 3.2, was created following the literature review. Chapter 4 took two CRTs that impact the ship in large and very different ways, with the largest reductions in $CO_2$ emissions, and modelled them in order to develop the Ship Impact Model (SIM), a model that can quickly model a wide range of CRTs.

This Chapter examines the initial outputs from the SIM using CRT data created in the Low Carbon Shipping - A Systems Approach (LCS) project, this is summarised in Table 6.1. The LCS project is discussed in more detail in Appendix A. This Chapter examines tools to improve the output from the SIM in order to check:

- How CRTs can be used in combination (in Section 6.3).
- How would a particular CRT be selected over another (in Sections 6.4 and 6.5).

Chapter 7 applies the tools that are developed in this Chapter following the intial results and examines a smaller number of CRTs in more detail with varying input parameters.

## 6.2 Initial Results using Carbon Dioxide Reducing Measures from the Low Carbon Shipping project

For the LCS project the model was run for large ocean-going ships that emit the largest amount of $CO_2$ emissions as described in Table 4.1 in Section 4.1. The operating profile and utilisation assumptions that were used are shown in Table 5.2 and Table 5.4, respectively, in Section 5.3.

More information about the modelling methods employed in LCS and the interfaces between the ship modelling and both the economic Shipping System Model and CRT level modelling are described in Appendix A and in a RINA conference paper and journal article [Calleya et al., 2012]. Additional background information on selected ship types is included in Appendix C.

### 6.2.1 Calculated Ship Impact Model Outputs

Table 6.1 gives an overview of the different CRMs that have been considered and shows only those results that were given in the literature review of CRMs (as in Table 3.2), in Chapter 3 and Chapter 4, or calculated by the SIM for LCS.

The $CO_2$ emission reductions from the SIM in Table 6.1 are deliberately at an overall ship level and do not consider the impact of the change in cargo due to a CRT on the ship (that is $CO_2$ emissions per cargo carried is not given). This allows the results to be compared better to the literature that was reviewed, which does not normally consider ship design and integration aspects.

| How CRM is modelled | Carbon Dioxide Reducing Measure (CRM) | Literature Review $CO_2$ reduction (if mentioned) | Ship Impact Model $CO_2$ reduction (if calculated) |
|---|---|---|---|
| Rejected - Outside the shipping system scope (defined in Section 1.2) | Ballast management and logistics | | |
| | Weather routing and heading control | 1% | |
| | Trim optimisation | 5% | |
| | Cold ironing | | |
| | Shaft generators | | |
| | Oil-based biofuel | | |
| Rejected - Better Alternative CRT | Gas turbines | | |
| | Steam systems | | |
| | Power distribution improvements | | 0.0% |
| Simple CRT Model | Improve propulsion coefficient | 4% | 0.0% to 4.9% |
| | Hull coatings | 4% to 6% | 1.7% to 5.4% |
| Simple and Complex CRT Model | Wind | 24% | 0.8% to 4.9% |
| Complex CRT Model | Air bubble lubrication | 15% | 1.5% to 4.8% |
| | Solar | | 0.0% to 3.7% |
| | Fuel cells for auxiliary power | | 1% to 12.2% |
| | Waste heat recovery | 3% | -0.1% to 0.8% |
| Primary Energy Source Options | Oil-based fuels | | |
| | Methane (LNG or CNG) | 25% | 16.6% to 24.8% |
| Operating | Cleaning and maintenance | 5% [Buhaug et al., 2009] | 0.4% to 1.3% |
| Assumptions | Operating speed profile | 20% to 30% | |
| Baseline Assumptions | Internal combustion engines | | |
| | Electricity | | |

Table 6.1: Carbon Dioxide Reducing Measures (CRMs) and how they could be integrated into a ship model including results from the SIM for LCS.

The variation in $CO_2$ emission reductions shown in Table 6.1 from the SIM were calculated from looking at the results for three different ship types and sizes; a 35 000 tonne deadweight 25 knot Panamax container ship, a 55 000 tonne deadweight 15 knot Panamax bulk carrier and a 130 000 tonne deadweight 15 knot Suezmax oil tanker.

The calculated $CO_2$ emission reductions for the full set of LCS CRTs for each of the three ships is in Appendix A in Tables A.1, A.2 and A.3, respectively.

### 6.2.2 Summary of CRT modelling assumptions used in LCS (shown in Table 6.1)

*This subsection contains a description of relevant work carried out by members of the RCUK Energy funded research project "Low Carbon Shipping: A Systems Approach" (LCS) and is not the authors own work, although any summary or conclusive statements that follow this work are that of the author. A brief oveview of the LCS project from a ship design perspective is given in Appendix A.*

The level of detail of each of the CRT studies carried out varied from literature reviews to detailed simulation and modelling (such as using CFD).

Cleaning and maintenance refers to hull maintenance and was modelled as a CRT in LCS, propeller polishing was also considered. Hull fouling is part of cleaning and maintenance, so in theory this could be higher than approximately 20% for a fouled ship. The assumptions associated with the condition of the ship are important.

Power distribution improvements include those aspects of power and/or energy distribution that could be improved. In LCS this included LED lighting and varibale speed pumps and fans; both of these caused a negligible reduction in $CO_2$ emissions at an overall ship level.

The propulsion coefficient improvement studies in LCS included a wide range of hydrodynamic devices and changes to the propeller; including:

- Wing pods.
- Pulling pods.
- Contra-rotating propeller.
- Vane wheel.
- Propeller section optimisation.

- Ducted propellers.
- Pre-swirl duct.
- Propeller upgrade.
- Propeller boss cap fins.
- Asymmetric rudder.
- Propeller rudder bulb.
- Optimise flow over openings.
- Covering of hull openings.

The majority of the propulsion coefficient improvements were estimated from the analysis of a specific ship and applied as a constant percentage change in propulsion efficiency, assuming that this is applicable to different ship types, sizes and design speeds. In contrast, air lubrication was implemented as primarily affecting frictional resistance this allows the effect of air lubrication to be approximated more accurately for different ship sizes and speeds, particularly at higher Froude numbers where the ratio of wave-making to frictional resistance changes.

Two types of air lubrication were examined in LCS; air bubble lubrication and air cavity lubrication. For this Thesis it was decided to adopt air bubble lubrication because the calculated $CO_2$ emission reduction for air bubble lubrication was consistently higher than for air cavity lubrication.

In LCS a contra-rotating propeller refers to having a larger propeller rotating in the opposite direction behind a smaller more conventional propeller, both around the same shaft. Although this arrangement may offer some benefits there is added complexity in the additional gearing and lubrication that is required.

The last two propulsion coefficient improvements, optimise flow over openings and covering of hull openings refer mainly to the bow thruster opening. It is also likely that improvements to the flow around the ship closer to the bow and further upstream could create further benefits downstream.

It was decided the fuel cells were to be used with LNG, however other fuel options, such as using a widely available oil-based fuel, may provide some benefits. The use of fuel cells is discussed in Sub-subsection 3.4.3.4. The fuel cell was used for auxiliary power. A fuel cell main engine with a gas turbine was also examined for use as a main engine to generate propulsion power, however it was found that large fuel cells were too voluminous and were impractical due to the large impact on cargo capacity relative to the displacement of the ship.

The calculated $CO_2$ emission reduction for methane (LNG or CNG) shown in Table 6.1 is integrated into the model as a fuel (or energy source) change, this is because fuel (or energy source) changes have a large effect on a ship design, and is based on the use of Liquid Natural Gas (LNG). The integration of different energy sources into the modelling process and LNG are discussed in Sections 4.4 and 4.2, respectively.

A Diesel-electric propulsion and power distribution system was not considered in LCS because this is normally less efficient than a hybrid arrangement [Buckingham, 2013] due to conversion losses, especially when maintaining an operating profile with a narrow band of speeds as with cargo-carrying ships. This is discussed in more detail in Sub-subsection 3.4.4.3.

Superstructure streamlining was also investigated in LCS but is not included in Table 6.1 because the $CO_2$ emission reductions are negligible from an overall ship perspective.

Optimisation of dimensions was also briefly examined in LCS and found to give very large reductions in $CO_2$ emissions, however this is a CRM that can be avoided by designing a ship correctly in the first instance so it was not included in Table 6.1. This is discussed in Subsection 3.2.1.

Costs of CRTs were difficult to obtain and keep consistent. As the range and type of costs can vary between each CRT, the cost of each CRT was represented as an inital purchase cost, Unit Purchase Cost (UPC), and an average annual cost, Through-Life Cost (TLC).

As well as clearly stating the assumptions for each CRT study, a confidence factor, between one and ten, for both the technology assumptions and the costing assumptions was used to try and quantify the inaccuracies associated wth the assumptions.

### 6.2.3 Summary and Conclusions

The objective here is to initially select what individual CRTs reduce $CO_2$ emissions and are cost-effective on a single ship basis to allow the selection of combinations of CRTs. This allows combinations of CRTs to be chosen economically. Some work done by others, such as 'Green Ship of the Future', focus much more on the detailed design of particular ship types and combinations of CRTs [Nielsen, 2009] [Schnack and Kristensen, 2009]. This may mean that individual CRTs are selected more from an engineering perspective rather than an economic perspective. These studies are useful, however not at an early design stage.

One of the benefits of the CRT studies from LCS is that the performance and integration aspects of different CRTs has been based upon independent sources that are unlikely to be biased. From the initial output from the SIM, shown in Table 6.1, the $CO_2$ emission reduction due to a CRT can vary considerably with ship type, size and speed. This variation is harder to capture from a literature review where most studies refer to the $CO_2$ emission reduction found in one specific case.

Combinations of CRTs were also not considered in LCS. For example, a duct and a pre-swirl stator used together, having a combined effect on the propulsion coefficient, could be combined into a single CRT. The effect of combinations of hydrodynamic CRTs on the ship is complex and they have to be modelled together. The interaction between CRTs is discussed in more detail in Section 6.3.

As mentioned in Subsection 3.2.2, the propulsion coefficient improvements are likely to be dependent upon speed or possibly Froude number because they effect the efficiency of the hull, the propeller and the interaction between the hull and the propeller. However, the propulsion coefficient improvements were specific to a few ships and described as the same percentage change in propulsion coefficient for all ships. Representing changes to the propulsion coefficient more accurately, likely based on speed or Froude number at least, would allow the analysis carried out by the SIM to be more accurate for a range of design assumptions and ship types, sizes and speeds.

Hydrodynamic and propulsor related CRTs that normally effect propulsion efficiency or resistance, such as Propeller Rudder Bulbs (PRBs), ducts, and pre-swirl and post-swirl devices, can be difficult to model because they operate in the complex flow around the ship:

- It is unclear if they can be scaled accurately to different ship types, sizes and speeds.
- When more than one is installed, in combinations with each other they interact directly with each other, for example the interaction between a pre-swirl and post-swirl device (see Section 6.3).

Some of the work in LCS was biased towards hydrodynamics and fuel cells even though these have small reductions in $CO_2$ emissions and high costs, respectively.

The calculated $CO_2$ emission reductions and performance for a particular ship depend on the initial design and operating assumptions of the ship. This means that it is important for the CRT studies to refer to the same baseline ships, this is also important when considering emissions regulations, relating to $SO_x$ and $NO_x$ as well as $CO_2$, and other regulations.

The potential large variation in $CO_2$ emission reductions shown in Table 6.1 with different ship sizes, types and speeds shows the large effect that different input assumptions, including the more uncertain operational assumpions, given in Section 5.3, can have on the output from the SIM.

At this stage there is enough information from the SIM outputs to make some decisions on which CRTs should be used based on a few parameters, such as the EEDI, UPC and TLC. However, there is not enough information to consider cost and operational performance together and how a CRT might be chosen by a ship owner or operator. It is necessary to consider:

- Qualitative barriers to selecting CRTs, as summarised in Section 5.8, these may be related to risk or safety. For example, for a different fuel it could depends on whether the available fuel infrastructure (bunkering facilities, etc.) has been developed.
- A time-frame is needed for investment otherwise most CRTs would appear to be profitable from a cost perspective because they eventually pay back their cost due to fuel savings. The profitability of a ship and CRT combination relative to other options would be a key parameter in the ship owners or operators decision as to whether or not to invest in a CRT.
- Performance and costs of combinations of CRTs - this could produce larger variations in performance and cost, especially with different operational assumptions.

The above points will be investigated in the following Sections:

- Considerations for using multiple CRTs (Section 6.3)
- Decision Support (Section 6.4)
- Profit or Cost to provide Economic Incentive (Section 6.5)

In order to mitigate the uncertainty it is possible to do a sensitivity analysis and quickly run the SIM for a range of design and operational assumptions to see what effect the design and operational assumptions have on the calculated $CO_2$ emissions and performance for different combinations of ships and CRTs. This is done in the next Chapter in Section 7.1 after developing a better understanding of what parameters may be important in this Chapter.

## 6.3 Considerations for using Multiple CRTs

The total $CO_2$ emission reductions from combinations of CRTs are not cumulative. They certainly cannot be added, as was done for NYK's Eco-ship in 2010 [NYK Group, 2010]. CRTs can be defined by their interactions between each other and the ship:

- Indirect interactions between CRTs (interact through the ship) can be modelled in the SIM as individual CRTs.
- Direct interactions between CRTs cannot be modelled in the SIM as individual CRTs but have to be modelled together.
- Incompatible CRTs cannot be modelled together in the SIM.

All combinations of CRTs are affected by indirect interactions. For example, this could be the combined impact on cargo from two CRTs or the effect of a change in efficiency of the propeller and propulsion coefficient due to decreased resistance due to a CRT. Some CRTs interact directly with each other. For example, a pre-swirl and post-swirl device may have a complex combined interaction that will likely have to be modelled or tested as a package of CRTs. Two CRTs affecting the same engine also may interact directly. Some CRTs cannot be used together, for example, if they demand different fuels or have a large impact on the topology of the ship.

In the first instance, if two or more CRTs have an overall effect on 'Resistance Parameters' or 'Engine or Fuel Parameters', as described in Table 5.5, then there is also potential for direct interactions as the CRTs are affecting similar aspects of the ship. All operational CRMs, such as operating speed, act as operating assumptions and can be combined with different CRTs. Service Parameters (such as deck space or energy demand from the ship) and Cost parameters do not cause incompatabilities and can easily be sized to meet the demand of multiple CRTs. The full list of parameters that a CRT can effect is shown in Table 5.5.

A compatibility or interaction matrix can be used to record the effects of combinations of CRTs. The SIM itself does not use a compatibility matrix because compatibility matrices have to refer to descriptions of specific CRTs that may depend on the assumptions made in the analysis of a particular CRT. The emphasis is more on flexibility and being able to quickly change CRTs and design and operational assumptions. Instead it is up to the user to decide which CRTs can be used together.

The function in the SIM that combines multiple CRTs can look for incompatabilities by checking what parameters are changed by multiple CRTs. If two CRTs try to change a particular parameter, such as by demanding different fuels for the same engine, shown in Table 5.5, then that may be an indication that two CRTs are incompatible.

A compatibility matrix is used when the individual ship outputs from the SIM are passed to the global shipping system model, they are summarised in the ship impact database as described in Appendix A. In the ship impact database the performance of different CRTs, as calculated by the SIM, in terms of $CO_2$ emissions, costs and cargo impact are described as being scalable with characteristics of the ship such as engine power or skin-friction resistance. Describing CRTs in this way summarises the output from the SIM and using a compatibillity matrix stops the shipping system model from putting CRTs together that will not work together. The compatibility matrix mainly consists of a yes or no flag for each possible CRT combination. Indirectly interacting CRTs can be modelled by the SIM in order to populate the compatibility matrix. It may also be possible to use a correction factor instead of a yes or no flag to record the effect of secondary ship impacts, such as changing cargo capacity or engine size on the calculated fuel consumption or $CO_2$ emissions.

### 6.3.1 Interface with CRT design

In order to model complex CRTs that interact directly it is better to model them together as a system of CRTs. For example, a duct and a pre-swirl stator could be combined into a single CRT system. In this way the ship and CRT interface can be used to describe a system of CRTs, in particular systems of hydrodynamic packages and engine packages. The disadvantage of this is that every possible combination of CRT will have to be modelled separately. Although this is normally unavoidable, especially when design decisions are involved, such as how much of a CRT to use with another CRT. Systems of CRTs for engines were modelled in detail in the ETI HDVE project (the ETI HDVE project is explained in Appendix B). As metioned in Section 5.4, pre-calculated look-up tables for a system of CRTs can keep the run time of the SIM short.

## 6.4 Decision Support Tools

Decision-making is the cognitive process leading to the selection of a course of action among alternatives [Lu et al., 2007]. Decision-making methods can be used to create a model to select the most suitable Carbon Dioxide Reducing Technologies (CRTs) for a given ship. Although the main objective of this Thesis is to examine ways to reduce $CO_2$ emissions, this will not be the main incentive of the ship owner or operator. The first Subsection, Subsection 6.4.1, starts by outlining some criteria that a ship owner or operator or Naval Architect may consider in order to select one CRT over another. Then Subsection 6.4.2 examines different decision-making methods that can be used with the outlined criteria and whether to use a decision-making process or not.

### 6.4.1 Criteria for selecting Carbon Dioxide Reducing Technologies

It has been summarised, initially in Section 2.8, that reducing costs and economic incentive is the main motivation for a ship owner or operator to invest in CRTs. When deciding on whether to adopt one CRT over another there are a number of considerations in order to ensure that there is a overall economic incentive at a low financial risk.

As mentioned in Section 2.4, there are also some some barriers to investing in CRMs from the ship owner or operators perspective, for example, safety will likely take precedence over reducing $CO_2$ emissions.

Considerations for adopting a CRM:

- To reduce operating costs (likely through a reduction in fuel consumption).
- To adhere to regulation (current or pending).
- To improve a brand or company image (this was discussed in Subsection 2.4.3).
- Safety of crew and ship.
- Compatibility with existing or supporting ship and infrastructure (for example, compatibility with port infrastructure, cold ironing or the amount of ship life remaining to consider a retrofit).
- Reliability.
- Technology Readiness Level (TRL) [Mankins, 2009].
- Contractual obligations.

Additional ship and CRT specific considerations to consider when using a CRT and when deciding on whether to choose one CRT over another CRT are:

- Safety and regulation in design and operation.
- Emission regulations in design and operation (such as EEDI, ECA and national regulations).
- Ease of installation/retrofit.
- Reliability/availability and maintainability.
- Ease of operation/crew training.
- Effect and predictability of toyage times and operational speed profile.
- Environmental image.
- Carbon dioxide equivalent emissions.
- Fuel/energy life cycle.

The impact of a CRT on the operating procedure of the ship is important to the ship operator. Reliability and voyage scheduling are important being aspects affecting the profitability of the ship. The cautious nature of some ship operators and owners, maybe partly due to the large investments and risk involved, this can make it more difficult for the adoption of CRTs with larger changes on the ship even though these can potentially cause higher reductions in fuel consumption and/or fuel cost.

For some stakeholders the percieved 'environmental image' is likely to be more important than the actual $CO_2$ emissions. The importance of brand and environmental image was discussed in Subsection 2.4.3.

Operating costs can also be expanded to include:

- Fuel price and cost differential between fuels (as highlighted when examining the use of natural gas as a fuel in Section 4.2).
- Operational costs not related to fuel use, such as ship charter cost or port costs.
- Install/purchase cost (long-term investment and cash flow considerations).

There are two issues with making decisions on which CRTs to adopt based on the listed CRT performance criteria; there is uncertainty associated with estimating each of the CRT performance criteria and the majority of the CRT performance criteria are behaviour or opinion based which makes them difficult to model.

### 6.4.2 Multi-Criteria Decision-Making

Multi-Criteria Decision-Making (MCDM) refers to making decisions in the presence of multiple and conflicting criteria [Lu et al., 2007]. MCDM can potentially be a valuable tool for marine design and allows some subjective considertion to be included, although it has not been widely used in design probably because of its simplicity in that all problems can be modelled on the basis of the same format [Sen, 1992].

In order to consider multiple CRT performance criteria it is necessary to weight the relative importance of each criteria, this will be based on opinion (likely the perception of an individual or group).

The Analytic Hierarchy Process (AHP), or another similar weighted multi-criteria decision matrix, such as a Pugh Matrix used in the ETI HDVE project (the ETI HDVE project is explained in Appendix B), can be used to reduce complex decisions to a series of one-on-one comparisons, and then synthesise the results [Lu et al., 2007]. The AHP uses pairwise comparisons to assess the relative importance of each criteria over another [Saaty, 1987]. Each criteria is given a weighting of 1, 3, 5, 7 or 9. 1 is used when two criteria are of equal importance and 9 is used when one criteria is extrememly important compared to another. The eigenvector is used to obtain the derived scale that makes use of all the dominence information in the matrix. AHP and similar methods using pairwise comparisons are quite widely known for decision-making, however there are some disadvantages to these methods. When comparing with respect to a property for which there is no established scale or measure, we are trying to derive a scale through comparing the objects two at a time. Since the objects may be involved in more than one comparison and we have no standard scale, but are assigning relative values as a matter of judgement, inconsistancies may well occur [Saaty, 1987].

For a ship and CRT combination we are comparing different criteria of the same system, where some criteria are directly and/or physically linked, in which case it may be important not to have too many criteria that are related, for example, for hydrocarbon based fuels $CO_2$ emissions correlate closely with fuel consumption.

In a more extreme case you can use psychological profiling, such as Belbin curves [Islei et al., 1999] to model how a normally conservative ship owner may respond to decisions. This would constrain any output too much because it will not provide any flexibility to ship owners and operators who have to respond to market demands.

### 6.4.3 Graphical representation of decisions and their outcomes

The MCDM methods discussed in Section 6.4.2 may add further uncertainty to the results from the SIM. The alternative is to represent lots of outcomes of all the possible decisions. If enough information is represented then the user of the information (possibly a ship owner or ship operator) can use their observations and decisions to find the information they need.

A simple way of doing this is by using a decision tree, maybe for different ship and CRT combinations. A decision tree is a predictive model to map observations about an item with conclusions about the items target value. Normally, each interior node corresponds to a variable and an arc to a child represents a possible value of that variable. A leaf represents the predicted value of the target variable given the variables represented by the path from the root [Lu et al., 2007]. The disadvantage of this is that all the possible outcomes will have to pre-calculated.

There are some benefits and considerations when representing a lot of information graphically or in a table [Tufte, 1990]:

- Visual displays are capable of simultaneously displaying a wide amount of information (unlike text).
- Presentation should be direct and obvious.
- High information graphics can convey a quantitive depth and sense of statistical integrity.
- Focus should be on data; good designs should be invisible to the user.

The train timetable shown in Figure 6.1 has numbers growing from both sides of a central stem in order to show trains running in different directions from the station, with the platforms 7-8 at the left and platforms 5-6 at the right (also note how numbers serpentine around a bend when times for the morning rush hour exceed the grid). The graphical elements in Figure 6.1 are multifunctioning.

Taking inspiration from the Japanese Train Timetable, Figure 6.1 and a few other sources there are a few techniques that can be used to represent lots of information clearly, as specified in the criteria above [Tufte, 1990]:

- A combined Micro and Macro graphical design can be used to represent data more elgantly, for example for a stem and leaf diagram, each data point simultaneously states

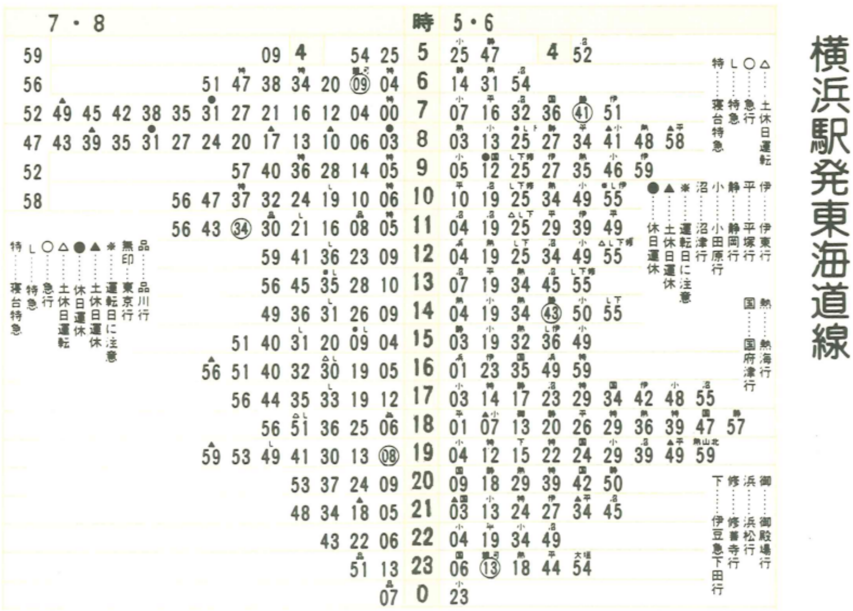



Figure 6.1: Tokaido Line at Yokohama Station, Sagami Tetsudo Company, 1985 timetable [Tufte, 1990].

its value and fills a space representing one counted unit. Macro and micro graphical designs can enforce both local and global comparisons and at the same time allow context switching.

- Small multiple graphics can be used where the same design structure is repeated for each image. Once a reader is familiar with one they can move from one image to the next, focusing on changes in information rather than changes in graphical composition.
- Access, such as text direction, can be used to divide the represented data, for example a back to back stem and leaf diagram are used to show trains in different directions.
- Some data and labels do not need to be repeated, for example the leading hour is only shown once and the minutes are stacked against the hour so that for trains that run more than once an hour the leading hours are not repeated.
- High density designs also allow viewers to select, narrate and recast and personalise data for their own uses.

Additionally it is also necessary to consider how much data is displayed, thin-data can prompt suspicion, such as about the accuracy of the data [Tufte, 1990].

It is envisaged that if the data is shown graphically in total five dimensions can be clearly shown.

By using a two-dimensional graph, another two dimensions can be added to the same graph by using colour, similar to a contour plot and changing the area of a data point, likely in a bubble (or scatter plot), and another dimension by repeating the same graph. Three-dimensional graphs can be difficult to read on two-dimensional paper, especially when it comes to interpreting areas and numbers from the graph and will not be used. Distinctions in shape value and size are important [Tufte, 1990], the areas of irregular shaped graphs can be misleading.

### 6.4.4 Selection of a decision-making method

Though MCDM may be useful to define a scoring system to compare ships and get a overall score it does mean that criteria have to weighted against each other so some are more important than others. The problem with this is the weighting criteria is something that should be defined by the decision-maker. Not using MCDMs is better in this case because it is possible to quickly calculate lots of conclusions and it avoids making assumptions about the importance of some criteria relative to others. If we want to keep a high fidelity and we consider the ability of the SIM to quickly carry out lots of runs to examine different ship and CRT combinations with design assumptions then it is better to pre-calculate lots of conclusions that can then be selected according to the users observations and preferences, like a decision tree.

It is better to represent information in a way that allows ship owners or operators or Naval Architects to compare the options that are important to them. In this case profit may be more important than cost as a decision varible. Quantatitive results for every CRT combination, possibly with different operational assumptions, will be calculated, such as profit and EEDI then a ship owner or operator or Naval Architect can then compare the profitability of different CRT combinations they will be able to adopt on a particular ship based on their own information that is specific to their situation, such as the infrastructure in the ports the ship uses, the route and/of a ship or how much risk they are willing to take.

The next Section, Section 6.5 will examine profit instead of cost as a decision variable, how the ship owner or operator or Naval Architect may make decisions and aim to answer the following questions:

- What does cost not capture compared to profit?
- What fidelity is required to ensure that the most profitable CRTs combinations are correctly selected by the SIM?
- How can a profit calculation be integrated with the SIM?

## 6.5 Profit or Cost to provide Economic Incentive

It was mentioned briefly in Section 6.4 that Operating costs can be expanded to include different types of fixed and variable costs. The unit cost can be given by Equation 6.1 [Stopford, 2009]:

$$\text{Unit Cost} = \frac{\text{Capital Cost of Ship} + \text{Operating Cost} + \text{Cargo Handling Cost}}{\text{Parcel Size}} \tag{6.1}$$

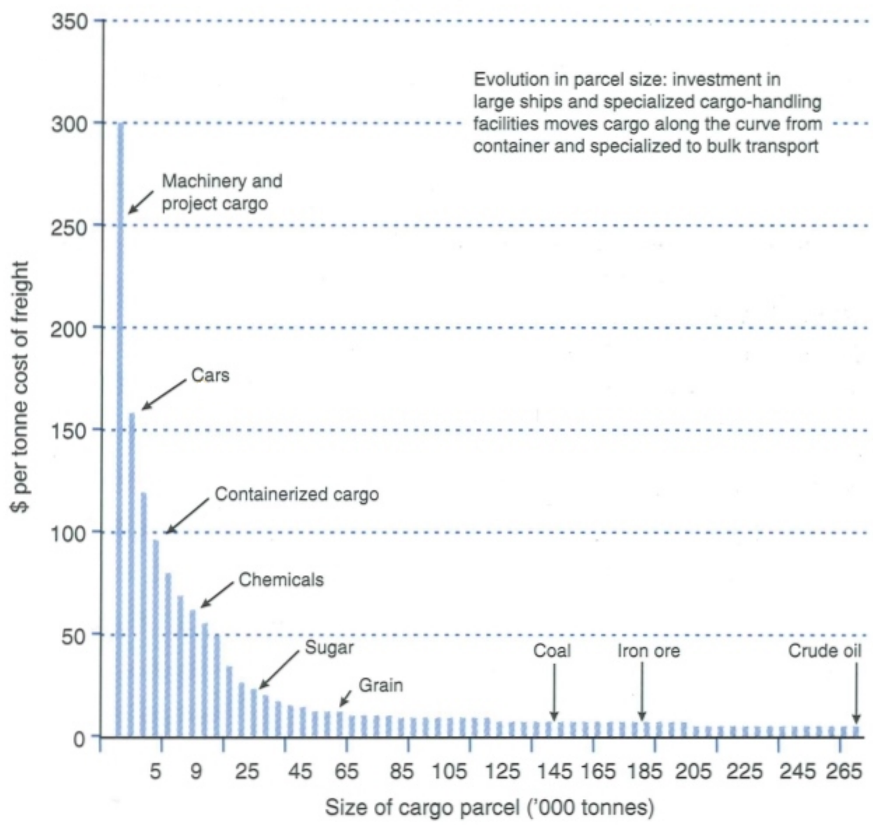



Figure 6.2: Shipping Unit Cost Function: parcel size and transport cost [Stopford, 2009].

Both operating costs (fixed costs of running a ship) and voyage costs (depends how ship is employed) are likely to be substantially higher for a old ship compared to a new ship, while economies of scale lead to lower unit costs for bigger ships [Stopford, 2009].

All the large international ships that are being considered here, container ship, bulk carrier, oil tanker and lng tanker, described in Appendix C, are highly specialised and may be able to achieve a lower unit cost, as described by Equation 6.1. A comparison between the unit costs of different types of cargo is shown in Figure 6.2. Flexible ships have a better chance of achieving a high level of loaded days at sea and deadweight utilisation because they can carrying many different types of cargo [Stopford, 2009].

### 6.5.1 Can a Maginal Abatement Cost Curve be used as a tool to select CRTs?

A Marginal Abatement Cost Curve (MACC) such as the one shown in Figure 6.3 produced by DNV in 2010 [Det Norske Veritas, 2010b]. According to the study shown in Figure 6.3 a lot of CRMs that already exist (every CRM below the axis will save money and should be adopted) are likely to get adopted towards 2030 because they are cost-effective. This may be a indicator for policy makers of the potential cost benefit to the shipping industry of reducing $CO_2$ emissions, however it is not a good indicator of what CRTs will get taken up on an individual ship basis. There is a gap between what policy should do and how it is implemented.

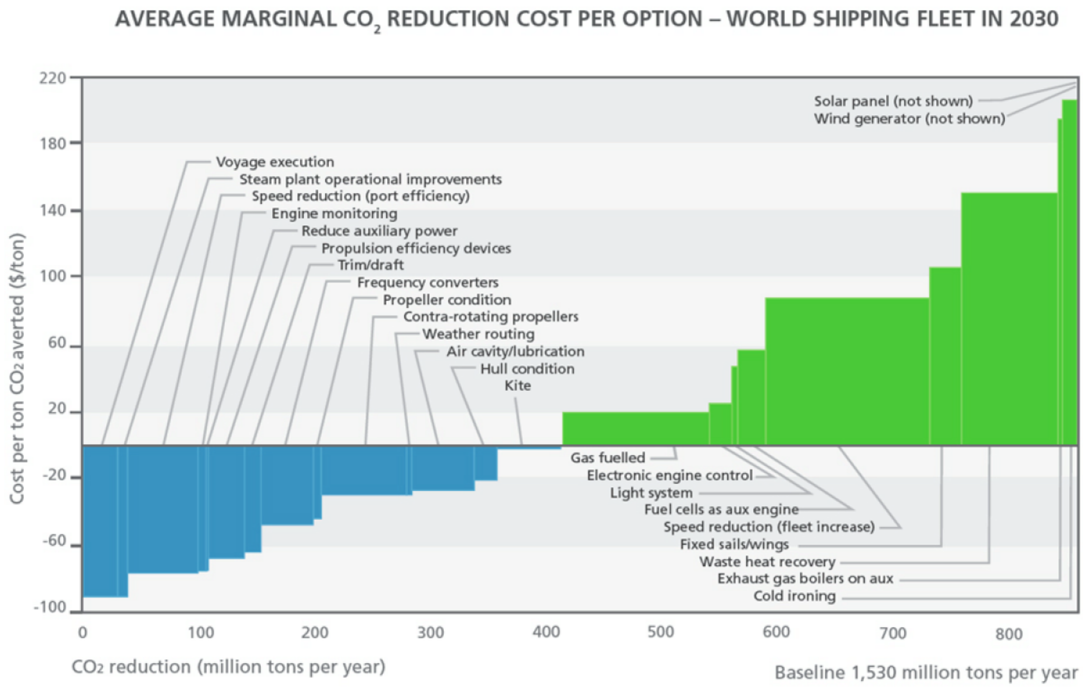



Figure 6.3: Average marginal $CO_2$ emission reduction cost per option - world shipping fleet in 2030 [Det Norske Veritas, 2010b].

MACCs were briefly mentioned in Section 1.3, a better way is needed to represent information to help choose which ship and CRT combinations should be adopted. Considering the way information is normally represented using a MACC [Kesicki and Ekins, 2012] and observations from modelling CRTs, in terms of interactions, uncertainty, etc., we can conclude that MACCs normally:

- Are set at a macro level, to represent markets or industries, and are not directly applicable at a individual ship level.
- Consider overall cost, this does not represent profitability.
- Assume a order in which CRMs are adopted.
- Do not capture split incentives, describes the problem that the investor in CRMs is not the person who benefits from the lower energy expenses [Kesicki and Ekins, 2012] and in this case other barriers that can occur at a individual ship level, such as the ability to retrofit to existing ships or response to regulation.
- Based on a forecast that is made at a specific time [Kesicki and Ekins, 2012].
- Used to assess measures independently to arrive at specific cost and abatement estimations, interactions go unconsidered when single measures are assessed separately [Kesicki and Ekins, 2012].
- Display no insight into the significant uncertainties related to the cost and $CO_2$ emission reduction estimates (normally only one MACC is represented) [Kesicki and Ekins, 2012] - giving design and operational assumptions would give additional context to the data represented in Figure 6.3.

In Figure 6.3 specifically speed is considered as a separate CRM rather than something that can effect other CRTs as discussed in this work; there is also a lack of information on uncertainty and assumptions.

### 6.5.2 Profit function from the Shipping System Model

*This Subsection contains a description of relevant work carried out by members of the RCUK Energy funded research project "Low Carbon Shipping: A Systems Approach" (LCS) and is not the authors own work, although any summary or conclusive statements that follow this work are that of the author. A brief oveview of the LCS project from a ship design perspective is given in Appendix A.*

Shipping is capital intensive so that the financial structure has a major impact on the cashflow [Stopford, 2009]. To understand what CRTs will be adopted it is necessary to know the cash flow, this requires revenue as well as costs, this can be used to calculate profit (or net present value).

The task of the ship designer is to evaluate the options considering both cost and operational performance; there are two different ways of doing this, net present value and required freight rate [Stopford, 2009]. A net present value calculation involves setting a projected cash flow for each of the options under consideration. Revenues and costs are projected on an annual basis and the net cashflow in each year is calculated. The annual cash flows are then discounted back to the present using a minimum accepted rate of return, for example 10% per annum, and then summed [Stopford, 2009]. The required freight rate method avoids the problem associated with calculating revenue by comparing the relative unit transport costs of different ship types [Stopford, 2009].

In order to have a better way to measure cost and operational performance at an indiiviual ship level a profit function that was used in the Shipping System Model, initially developed for LCS, which examines the cost and performance of shipping at an international level was adapted to be used in the SIM at an individual ship and CRT combination level. The Shipping System Model and the interaction between the Shipping System Model and the Ship Impact Model (SIM) are explained more in Appendix A.

There are three main components to the profitability model that are used in a net present value calculation; Operational cost ($C$), Capital costs ($C_0$) and an investment calculation.

Equation 6.2 shows the net present value calculation that is used:

$$\text{Net Present Value} = C_0 + \frac{\sum_{t=0}^{T}(R - C)}{(1+d)^T} \tag{6.2}$$

Where:

- $C_0$ is the capital cost of the CRT. The net present value calculation is carried out for both the baseline ship and the modified ship and the difference between them is calculated, this means that the capital cost of the vessel itself is cancelled out.
- $R$ is the revenue that the ship will generate, this will include secondary changes due to a CRT such as a change in deadweight resulting in a change in the charter rate of the ship.
- $C$ is the cost, this will include primary changes due to a CRT such as change in operating cost including fuel cost.
- $d$ is the discount rate.
- $T$ is the number of years over which the evaluation is applied, this is also termed the investment period of the CRTs that are being examined.

The average speed and average daily fuel consumption are calculated based on the operating profile of the ship and are inputs to the profitability function. The average speed is used to work out the the transport supply in the profitability function. The time spent in each condition, loaded at sea, in ballast at sea and in port, has to be consistent between the performance calculations and the probability function. This is so that the fuel consumption, the amount of voyages carried out and the port costs are consistent.

As well as getting the average speed and calculated fuel consumption from the model the following input information is also required for each year that is examined:

- Bunker costs for each fuel.
- Operational and utilisation data (this includes the capacity loaded, time in each condition and time in ECAs).
- Port costs.
- Regulation applied (if any), such as $SO_x$, $NO_x$ or $CO_2$ regulation.
- New build price and Charter cost.

The revenue is calculated from the transport supply and freight rate (for a minimum expected return) from the utilisation assumptions, costs and a discount rate of 10%. The investment period, represented by $T$ in Equation 6.2, will depend on how the ship is owned and operated and the source of capital. The source of capital could be; private funds, commercial bank finance, capital markets or standalone structuress [Stopford, 2009]. As the investment period can easily vary between ships and is not well known it is a operational assumption that can be changed in the SIM.

The proftability function also adds additional exhaust gas treatment, such as SCR, to the ship if required by the emission regulation that has been forecasted for the particular year that is being examined. Although this does not need to be used for ships in the short term as defined by the scope of this work, defined in Section 1.2. However, adding a SCR causes both a addiitional cost and a small (estimated to be 2%) decrease in efficiency and hence a small increase in $CO_2$ emissions.

Going to this level of detail for profitability may be slightly beyond the initial scope, defined in Section 1.2, however this is necessary in order to capture the secondary economic effects, such as a more fuel efficient ship having a higher charter rate and the economies of scale benefits of larger ships.

## 6.6 Summary and Conclusions

As examined in Subsection 6.4.4 and Section 6.5, it is better to represent information in a way that allows ship owners or operators or Naval Architect to compare the options that are important to them. Net present value considers cost and operational performance. Profit (in terms of net present value) will be calculated for every CRT combination, possibly with different operational assumptions, then a ship owner or operator or Naval Architect can then compare the profitability of different CRT combinations they will be able to adopt on a particular ship based on their own information that is specific to their situation, such as the infrastructure in the ports the ship uses, the route and/of a ship or how much risk they are willing to take. Though it is also necessary to consider that minimising EEDI and minimising $CO_2$ are may lead to different solutions.

Taking into account what has been discussed so far in this Chapter and in the objectives that were discussed in Chapter 1, in Sections 1.2 and 1.3, in terms of selecting multiple combinations of ships and CRTs we can summarise that:

- Multiple CRTs that interact indirectly can be examined in the SIM.
- MCDM methods such as AHP can be used to consider multiple design criteria, however they can add further uncertainty to the outputs because you are assuming that the same weighting criteria for each decision maker and for each ship and CRT combination.
- A predictive model, such as a decision tree, can be used to map observations from the user of the model to pre-calculated conclusions, though such a model would represent more information than one single user would require.
- Small multiple graphics can be used where the same design structure is repeated for each image. Once a reader is familiar with one they can move from one image to the next, focusing on changes in information rather than changes in graphical composition.
- Current ways of representing CRTs are unsuitable and lack information, some of the drawbacks of existing work was discussed in Subsection 6.5.1 of this Chapter and in Section 1.3 in Chapter 1.
- A net present value calculation allows the Naval Architect to evaluate the options considering both cost and operational performance [Stopford, 2009].

In terms of graphs, it was envisaged in Section 6.4 that five dimensions can be shown by using multiple graphs. Each small graphic within multiple graphics can be used to represent each CRT combination. The result of changing design and operational assumptions associated with each CRT can be shown on the same graph in order to show the variability in CRT performance (could be in terms of profit, cost or $CO_2$ emissions) with changing design and operational assumptions.

Ship design and the SIM are complex and made up of lots of interlinked systems and functions, this can be seen by examining the overall program flow diagram shown in Figure 5.2. It is difficult to find one objective function that can be used to maximise profit by changing the decision variables whilst keeping within the constraints. It is easier to use the ability of the SIM to carry out a sensitivity analysis, quickly calculating the results of many ship and CRT design combinations with varying design and operational assumptions.

## Chapter 7

# Detailed Sensitivity Analysis

## 7.1 Sensitivity Analysis and Downselection of CRTs

As mentioned in Section 6.6, it is easier to use the ability of the Ship Impact Model (SIM) to carry out a sensitivity analysis (by quickly calculating the results of many ship and CRT combinations with varying design and operational assumptions) than it is to derive precise assumptions and/or objective functions ab initio. The problem that may occur with this approach is that the input parameters may not always be consistent with each other so it is possible that some results could be unrealistic as combinations of extreme assumptions are used together. There are two consequences of this; the constraints defined by the baseline ship may not be met and/or the performance of the ship could be underestimated (generally, too far from the constraints), this may be more likely with bigger changes from the baseline ship, such as more CRTs used in combination.

In order to carry out a sensitivity analysis of multiple CRTs, five CRTs were selected from the calculated individual $CO_2$ emission reductions shown in Table 6.1, the cost and the calculated profit. It was also necessary to consider:

- CRTs are in use at the moment and likely to be used in the future.
- CRTs with a low TRL.
- CRTs that can be combined (to achieve a larger reduction in $CO_2$ emissions).
- CRT that have performance characteristics that can be easily modelled and/or accurately approximated (possibly because they are simpler, have a high availability or are well investigated in LCS and in this Thesis).

### 7.1.1 Comparison of Carbon Dioxide Reducing Technologies that effect the propulsion coefficient

The CRTs relating to the propulsion coefficient directly interact with each other and have to be modelled together. For example, two CRTs such as a pre-swirl and post-swirl device should both be fitted to the same ship or CFD model in order to correctly capture the change in performance. No CRTs were modelled in combination in LCS and different CRT that effect propulsion coefficient cannot be combined in the Ship Impact Model (SIM) because the direct interaction between the CRTs cannot be captured in the SIM, as explained in Section 6.3. It was decided to compare the different CRTs that effect the propulsion coefficient and select the single most profitable CRT, this can then be combined with other CRTs in the SIM that interact indirectly (possibly by affecting a different part of the ship, such as those CRTs that affect the engine) and can be used in combinations of CRTs.

A comparison between the different propulsion coefficient (or hydrodynamic) CRTs for three different ship types, that was done for LCS, is shown in Table 7.1, assumed a two year investment period.

*All the information in Table 7.1 has been calculated based on data supplied by other members of the LCS project. From this data there is no impact on Through-Life Cost (TLC). The calculated impact on the ship, normally represented as a percentage changes in propulsion coefficient or calculated from the overall change in $CO_2$ emissions, was assumed to be applicable to different ship types, sizes and speeds, despite the calculated ship impact being based on one or two point designs. This assumption maybe significant for some hydrodynamic devices, whose performance varies with speed. Costing is also an issue. With no better scalable data readily available it is being used with the purpose of demonstrating the model, absolute results using the CRTs that effect propulsion coefficient (hydrodynamic CRTs) should be interpreted with care. The baseline ship was also not clearly defined in the LCS project.*

| Bulk carrier Carbon Dioxide Reducing Technologies (CRTs) | Propeller Section Optimisation | Pre-swirl Duct | Propeller Boss Cap Fins | Asymmetric Rudder | Propeller Rudder Bulb |
|---|---|---|---|---|---|
| Estimated EEDI | 6.44 | 6.42 | 6.44 | 6.46 | 6.46 |
| Reduction in $CO_2$ emissions | -0.9% | -1.5% | -0.9% | -0.5% | -0.5% |
| Reduction in $CO_2$ emissions per cargo capacity | -0.9% | -1.4% | -0.9% | -0.5% | -0.5% |
| Unit Purchase Cost (UPC) | $113876 | $290500 | $142096 | $139440 | $360 |
| Through-Life Cost (TLC) | $0 | $0 | $0 | $0 | $0 |
| Change in Profit | -$18617 | -$132537 | -$44447 | -$84397 | $42899 |
| Container ship Carbon Dioxide Reducing Technologies (CRTs) | Propeller Section Optimisation | Pre-Swirl Duct | Propeller Boss Cap Fins | Asymmetric Rudder | Propeller Rudder Bulb |
| Estimated EEDI | 35.123 | 35.188 | 35.126 | 35.236 | 35.239 |
| Reduction in $CO_2$ emissions | -1.3% | -1.1% | -1.3% | -0.7% | -0.7% |
| Reduction in $CO_2$ emissions per cargo capacity | -1.3% | -1.0% | -1.3% | -0.7% | -0.7% |
| Unit Purchase Cost (UPC) | $504504 | $1287000 | $94500 | $617760 | $3037 |
| Through-Life Cost (TLC) | $0 | $0 | $0 | $0 | $0 |
| Change in Profit | -$105987 | -$887645 | $269278 | -$385771 | $176867 |
| Oil tanker Carbon Dioxide Reducing Technologies (CRTs) | Propeller Section Optimisation | Pre-Swirl Duct | Propeller Boss Cap Fins | Asymmetric Rudder | Propeller Rudder Bulb |
| Estimated EEDI | 5.953 | 5.922 | 5.953 | 5.976 | 5.976 |
| Reduction in $CO_2$ emissions | -0.4% | -0.7% | -0.4% | -0.2% | -0.2% |
| Reduction in $CO_2$ emissions per cargo capacity | -0.4% | -0.7% | -0.4% | -0.2% | -0.2% |
| Unit Purchase Cost (UPC) | $265776 | $678000 | $335863 | $325440 | $840 |
| Through-Life Cost (TLC) | $0 | $0 | $0 | $0 | $0 |
| Change in Profit | -$37498 | -$300057 | -$101647 | -$193968 | $103129 |

Table 7.1: Comparison of CRTs that effect propulsion coefficient (or hydrodynamic CRTs) using data from LCS.

It is sometimes possible to see which CRTs will perform better in terms of profitability by comparing the cost of CRTs with the same or very similar emissions reductions. Both Asymmetric Rudder and Propeller Rudder Bulb have the same effect on each of the three ships in terms of fuel consumpton and $CO_2$ emissions, however the asymmetric rudder is much more expensive in terms of purchase cost, so in this case it is possible to rule out the asymmetric rudder without having to calculate profitability. Although it is possible to use an asymmetric rudder and propeller boss cap fin together, these components should be designed to work together to have a higher $CO_2$ emission reduction potential.

Propeller section optimisation was ruled out because the calculated $CO_2$ emission reductions are based on the assumption that the original ship propeller was not selected and designed correctly, this means the potential savings from different ship types could vary considerably depending on the initial assumptions.

The decision of which CRT to use to improve the propulsion coefficient is between a Pre-Swirl Duct, Propeller Boss Cap Fins and Propeller Rudder Bulbs. Which one to adopt depends on the investment period. A Pre-Swirl Duct may have a high potential reduction in overall cost only if the investment period is more than approximately 15-20 years long, otherwise it is likely to result in the biggest loss.

The Propeller Rudder Bulb (PRB), a bulb fitted to the rudder directly behind the propeller boss, was chosen for this analysis based on the data in Table 7.1 because even with a short two year investment period the Propeller Rudder Bulbs (PRBs) can make a profit, the Propeller Boss Cap Fins were only able to pay back their cost on the container ship, which has the highest design speed of the three ships and hence uses the most fuel. Although the $CO_2$ emission reduction is slightly smaller than the alternative Propeller Rudder Bulb (PRB) it is significantly less expensive. It is very likely that the large difference in cost is an error in the costing figure from LCS this could be due to the costs being described incorrectly (possible taken from a different context or type of ship) and not being scalable with different ship sizes. This data is uncertain but for the purpose of demonstrating the model, the CRT that appears the best, the Propeller Rudder Bulb (PRB) will be used.

The majority of the calculated profit values in Table 7.1 are negative. This can be contrasted with the fact that the CRTs under consideration are in service on many operational ships. This indicates that the model is not reflective of reality. Given that the ship designs were validated (in Section 5.6) and accepting that the CRTs were modelled with sufficient accuracy by the subject matter experts in LCS. The most likely cause is that the assumed investment period is too short, and that some ship operators have a longer investment period.

### 7.1.2 Selection of CRTs that have a high reduction in $CO_2$ emissions

Wind and LNG were selected on the basis of having the highest savings at a not too high a Unit Purchase Cost (UPC) (for most CRTs Through-Life Cost (TLC) are small compared to Unit Purchase Cost (UPC)). In Table 6.1, after wind and LNG the next biggest reduction in $CO_2$ emissions is from using fuel cells for auxiliary power. However, the Unit Purchase Cost (UPC) of fuel cells was too high. The baseline ship also uses oil-based fuel and the fuel cell uses LNG. Part of the calculated $CO_2$ emission reduction, shown in Table 6.1, comes from reducing the carbon content of the fuel when changing to LNG.

In Table 6.1 using the CRT model created for LCS the calculated $CO_2$ emission reduction from wind has been greatly underestimated, between 0.8% and 4.9%, this compares to around 27.5% in the initial analysis of wind in Section 4.3 and a $CO_2$ emission reduction of 23% in the literature review. The assumptions for the calculated $CO_2$ emission reductions from sails from LCS were not made clear (similar to the problems described in Subsection 7.1.1) but the impact of sails on the ship in LCS was modelled based on a literature review rather than a calculation of actual sail area. So instead of using the CRT model created for LCS the study in Section 4.3 was used as a basis to write a better CRT model for wind, using a wing-sail arrangement. Integrating the wind model in Section 4.3 into the SIM, specifically by using parameters for deck area and change in thrust/resistance requirement, means that the sails can be properly sized depending on the ship size and type. Also the secondary effects that were not calculated in Section 4.3, such as the change in performance of the propeller due to being lightly loaded, can be calculated. Smaller savings will be calculated for container ships and other ship types that are assumed to have less available deck space for CRTs. It may also be necessary to make trade-offs with structure, stability and cost (as discussed in Section 4.3), this is not considered in the CRT model. It is assumed that as many sails are installed as the ships deck space will allow.

Waste heat recovery was selected because it is currently used on many ships, mainly larger ships that operate at higher speeds, and can create good $CO_2$ emission reductions, compared to the other CRTs that were examined, behind wind and LNG, the calculated $CO_2$ emission reductions over an operating profile appear much lower it is already used to some extent on larger faster ships.

### 7.1.3 Downselection of CRTs

Only five CRTs were chosen because all possible combinations of five CRTs, from fitting zero to up to five CRTs to a ship, amounts to 32 different ship and CRT combinations. The CRTs that were selected are:

- Wing Sail (WS)
- Propeller Rudder Bulb (PRB)
- Waste Heat Recovery (WHR)
- Air Bubble Lubrication (ABL)
- Liquid Natural Gas (LNG)

### 7.1.4 Alternative operating speed profile

A more optimistic, no slow steaming, operating profile, shown in Table 7.2, was used to find the maximum possible $CO_2$ emission reduction for some CRTs by using an operating profile that is better matched to the design speed of the ship. The standard operating profile, in Table 5.2, was modified to reduce the amount of slow steaming time, time at 25% MCR and 37.5% MCR to zero. Subsection 5.3.2 should be referred to for the assumptions associated with the operating profile.

This mainly effects container ships as the other ship types that were investigated spend very little time slow steaming.

| Activity | Speed calculation | Bulk carriers | Container carriers | Oil tankers | LNG tankers |
|---|---|---|---|---|---|
| Low speed | 0.3×Design speed+0.5 | 2% | 3% | 3% | 3% |
| (manoeuvring) | 0.4×Design speed | 1% | 3% | 2% | 1% |
| Slow steaming | Speed at 25% MCR | 0% | 0% | 0% | 0% |
| | Speed at 37.5% MCR | 0% | 0% | 0% | 0% |
| Contracted speed | Design speed−3 knots | 66% | 67% | 25% | 33% |
| (cruising speed) | Design speed−1.5 knots | 23% | 26% | 66% | 60% |
| Full speed (bad weather) | Speed at 100% MCR | 8% | 1% | 4% | 3% |

Table 7.2: Alternative (no slow steaming) operating profile that was used in the sensitivity analysis (modified from Table 5.2).

### 7.1.5 Selection of variables to change in sensitivity analysis

In total 69120 runs; combinations of ship, CRTs and design and operational assumptions, were carried out in order to examine the effect that the more uncertain design and operational parameters have on CRT performance. The parameters that were varied are detailed in Table 7.3 and were selected due to having a high uncertainty as well as a large potential effect on the performance of CRTs.

| Parameter Type | Parameter | Min | Max | Total | Notes |
|---|---|---|---|---|---|
| Ship description | Ship type | | | 3 | Bulk carrier, container ship and oil tanker. |
| | Ship design speed | | | 2 | 10 and 15 knots for bulk carriers and oil tankers and 20 and 25 knots for container ships. |
| | Ship size | | | 2 | Smallest and largest widely used ship sizes. |
| Design | Design engine rating | 75% | 95% | 3 | Varied in SIM. |
| Operation | Resistance increase from fouling | 0% | 48% | 5 | Varied in SIM. |
| | Auxiliary power utilisation | 20% | 80% | 2 | Assumed the same percentage of installed power used for all ships. |
| | Operating profile | | | 2 | With slow steaming and without slow steaming. |
| CRT | Ship and CRT combinations | | | 32 | Varied in SIM. |
| Profitability | Investment period | 4 | 12 | 3 | |
| | Total runs | | | 69120 | 480 runs in the SIM (15 assumptions for each ship and CRT combination) and 144 outside the SIM. |

Table 7.3: Design, operational and profitability parameters that were changed in the ship and CRT sensitivity analysis.

In Table 7.3, “Varied in SIM” means that this parameter was varied in the SIM so that the calculation could be carried out within each required run of the SIM without having to re-run the model. These calculations are calculated in the SIM by having a loop that re-runs the model for different assumptions. A maximum of two assumptions can be varied within a single run of the SIM this is partly because only two dimensions can be represented in the output spreadsheet (different sheets are used for different CRTs combinations). 144 runs of the SIM were carried out with 480 runs being carried out in each run of the SIM. Additionally there are some other design assumptions that could be changed but these were kept constant, these are candidates for further study, see Section 8.3:

- Heat energy utilisation.
- Endurance/range - important consideration, with operational speed profile, when considering different fuels.
- Design speed of hull.
- Shaft generator - Power-Take-In (PTI) or Power-Take-Off (PTO).
- Controllable Pitch Propeller.

Heat energy is used for auxiliary boilers and cargo heating, while the endurance/range of a vessel may be an important consideration when changing fuels, for example, from oil-based fuel to natural gas, as mentioned in Section 4.2.

### 7.1.6 Ship Impact Model post processor

A separate post-processor was written to filter the results and display them in a way to make it easier to identify patterns from a copious amount of data. There are two stages to the post-processor; a validation check and plots of the results themselves.

The first stage of the post-processor filters out any invalid ships that either do not meet the required design speed or have too much installed power, a value of 5% below the design MCR is used.

Having too much installed power due to some combinations of assumptions and CRTs (as the implementation of a CRTs can move a ship away from or closer to its design condition) is likely to cause a ship to be less efficient at its design speed and maybe at lower speeds and will also lead to an unrealistically high EEDI.

Invalid ships can occur because the input assumptions were considered independently of each other and can be caused by a change in the performance of a ship once a ship has been modified by a CRT. This does not matter very much because many runs can be carried out quickly, in practice or for detailed design the invalid ships would require another iteration of the design spiral with the CRT fitted. More care must be taken with larger changes to the baseline ship, such as when multiple CRTs are fitted. This is where exploring lots of designs can be useful. For example, some baseline ship designs that initially did not reach their design speed may become viable once they have been modified by CRTs.

The process of generating lots of designs and having some that are not viable is similar to how decision support software was used with the ship design software, Paramarine [QinetiQ GRC, 2013], in order to facilitate the initial options and cost the initial design stage [Burger and Horner, 2011]. The difference is that this was used during the ship design spiral so that invalid designs were not balanced, in this work we are assuming small changes to existing balanced designs, and Burger and Horners study was for a Royal Fleet Auxiliary ship, which uses a mix of commercial and military standards and generally has a more complex topology compared to a commercial ship.

## 7.2 Results

The results are shown in Figures 7.1, 7.2, 7.3, 7.4 and 7.5. In each Figure each dot represents a unique combination of ship type, size and design speed, CRT and design and operational parameters (such as operational speed profile). The different shades of grey show the percentage increase in skin-friction resistance due to the fouling associated with that particular combination, with black representing a 0% increase in skin-friction resistance and light grey representing a 48% increase in skin-friction resistance. The fouling condition was represented as a dimension in the outputs because the assumed fouling condition was deemed to be one of the assumptions that has the single largest impact on the performance of a ship and CRT combination compared to other variable design and operational assumptions. The additional resistance due to fouling is applied as a constant percentage increase in skin-friction resistance in the operational condition only, in the design condition an allowance for fouling and deterioration is set by the percentage design main engine MCR (design MCR is also a parameter that is varied). Table 7.3 shows the parameters that were varied in the sensitivity analysis that was carried out.

The size of the data points, in Figures 7.1, 7.2, 7.3, 7.4 and 7.5, represents the assumed investment period, this was 4, 8 or 12 years, with the bigger points represented 12 years.

It is possible the investment period can vary significantly between specific ships and can be independent from the ship specification. It was not possible to clearly show all the different ship design and operational assumptions for each CRT combination shown in the graphs because there are too many dimensions to display on one Figure. Only two dimensions could be labelled clearly so two assumptions, increase in skin-friction resistance due to fouling and investment period, that were thought to have a large effect on profitability were represented. However, the results of several different changing parameters are shown, as described by Table 7.3.

Out of the total 69120 runs that were carried out there were 5232 valid ship and CRT combinations, which were capable of meeting the required design speed and did not exceed the design speed when the main engine was operating at 5% below its design MCR.

In Figures 7.1, 7.2, 7.3, 7.4 and 7.5 multiple, similar graphs, with the same axes have been used to represent different combinations of CRTs.

Changing the design and operational assumptions has implications for the baseline ships. This can be seen in Figures 7.2, 7.3, 7.4 and 7.5, where absolute results are plotted against at least one axis, except for Figure 7.1 where a percentage change in profit is plotted against a percentage change in $CO_2$ emissions. This is because the unmodified baseline ship should be compared against the same ship that is modified by a CRT combination with the same design and operational parameters in order to examine how the CRT combination performs.

The results should be interpreted carefully because many varying ship types, sizes and speeds with different design and operational parameters are represented together on the same Figures. It is also necessary to understand how the results were calculated. Consider Figure 7.4, the hull fouling as a change in skin-friction resistance, shown as differerent shades of grey in Figure 7.4, appears to change the EEDI for different CRT combinations. However the EEDI is calculated based on the design condition and will not be effected by the hull fouling. It is more likely that for some specific ships designs the high level of hull fouling has some ships that may of been initially invalid as a baseline ship valid when combined with CRTs, these baseline ships were likely initially invalid because too much power was installed. Another indicator for this is that for the baseline ship in Figure 7.4 (with no CRTs fitted) you cannot see high levels of fouling having a impact on the EEDI.

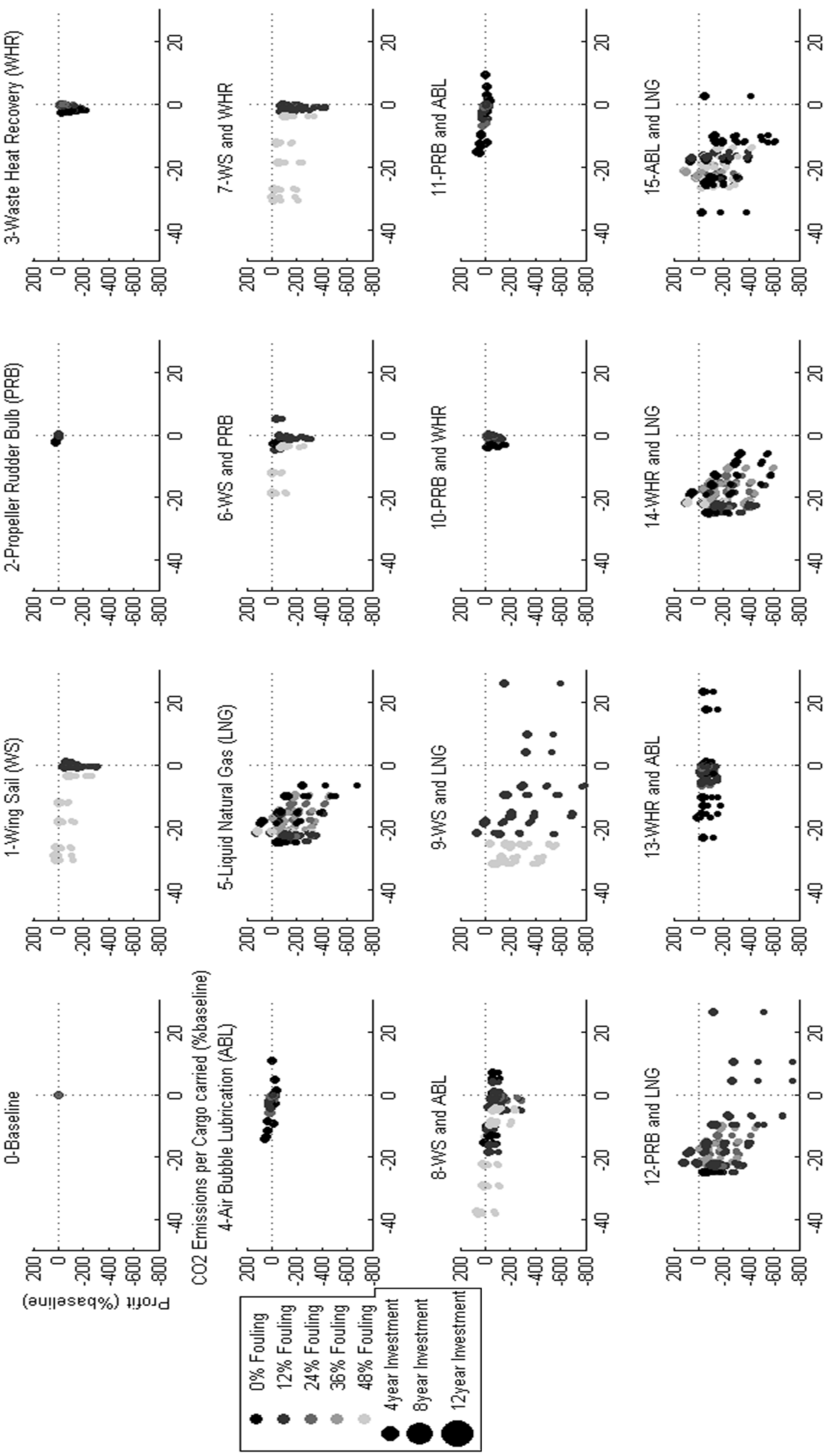
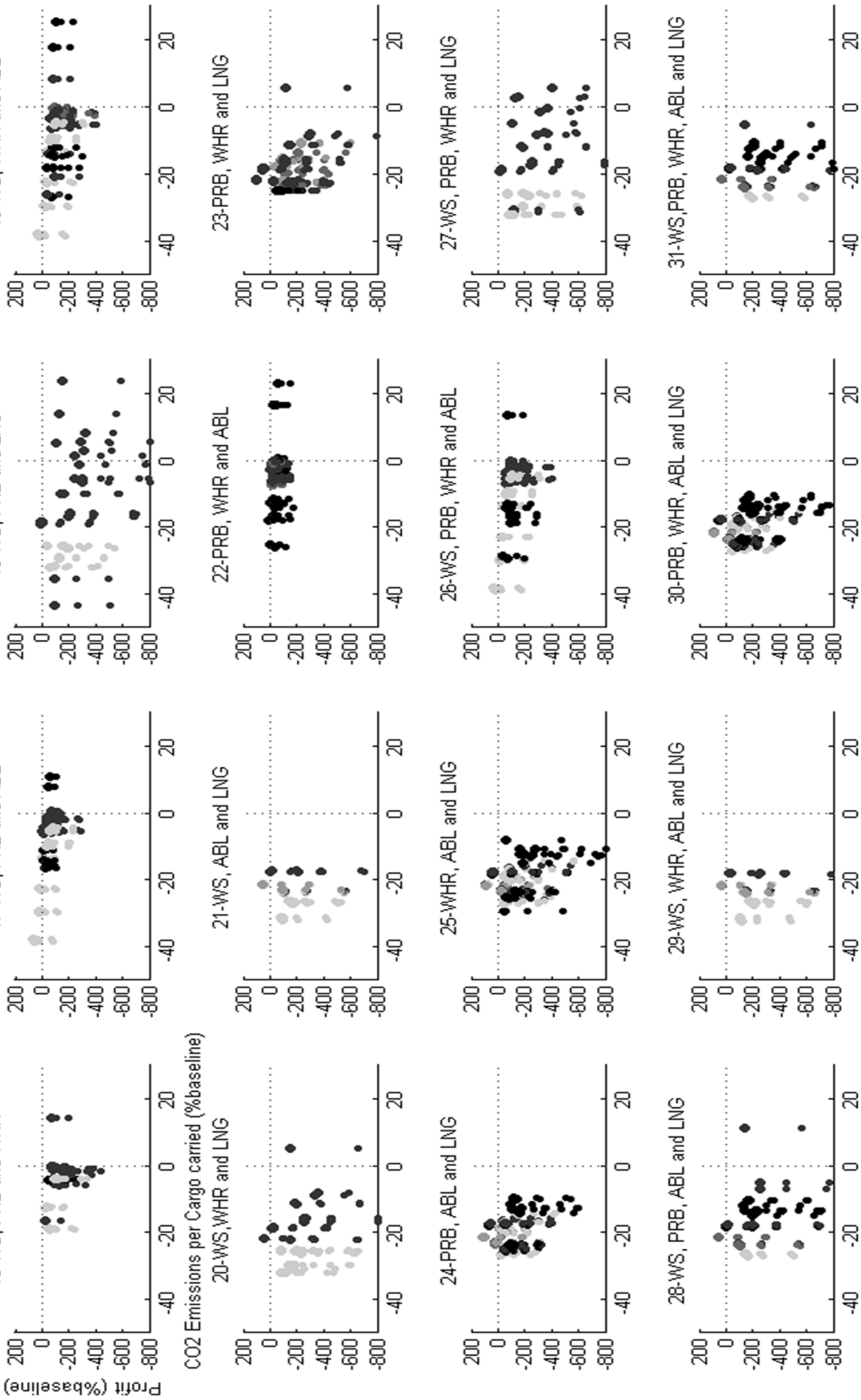



Figure 7.1: Percentage change in profit against percentage change in ratio of mass of $CO_2$ emissions to cargo for each CRT combination (change relative to a baseline ship) - the largest points represent an investment period of 12 years (two pages).



16-WS, PRB and WHR
17-WS, PRB and ABL
18-WS, PRB and LNG
19-WS, WHR and ABL
20-WS,WHR and LNG
21-WS, ABL and LNG
22-PRB, WHR and ABL
23-PRB, WHR and LNG
24-PRB, ABL and LNG
25-WHR, ABL and LNG
26-WS, PRB, WHR and ABL
27-WS, PRB, WHR and LNG
28-WS, PRB, ABL and LNG
29-WS, WHR, ABL and LNG
30-PRB, WHR, ABL and LNG
31-WS,PRB, WHR, ABL and LNG
CO2 Emissions per Cargo carried (%baseline)
Profit (%baseline)

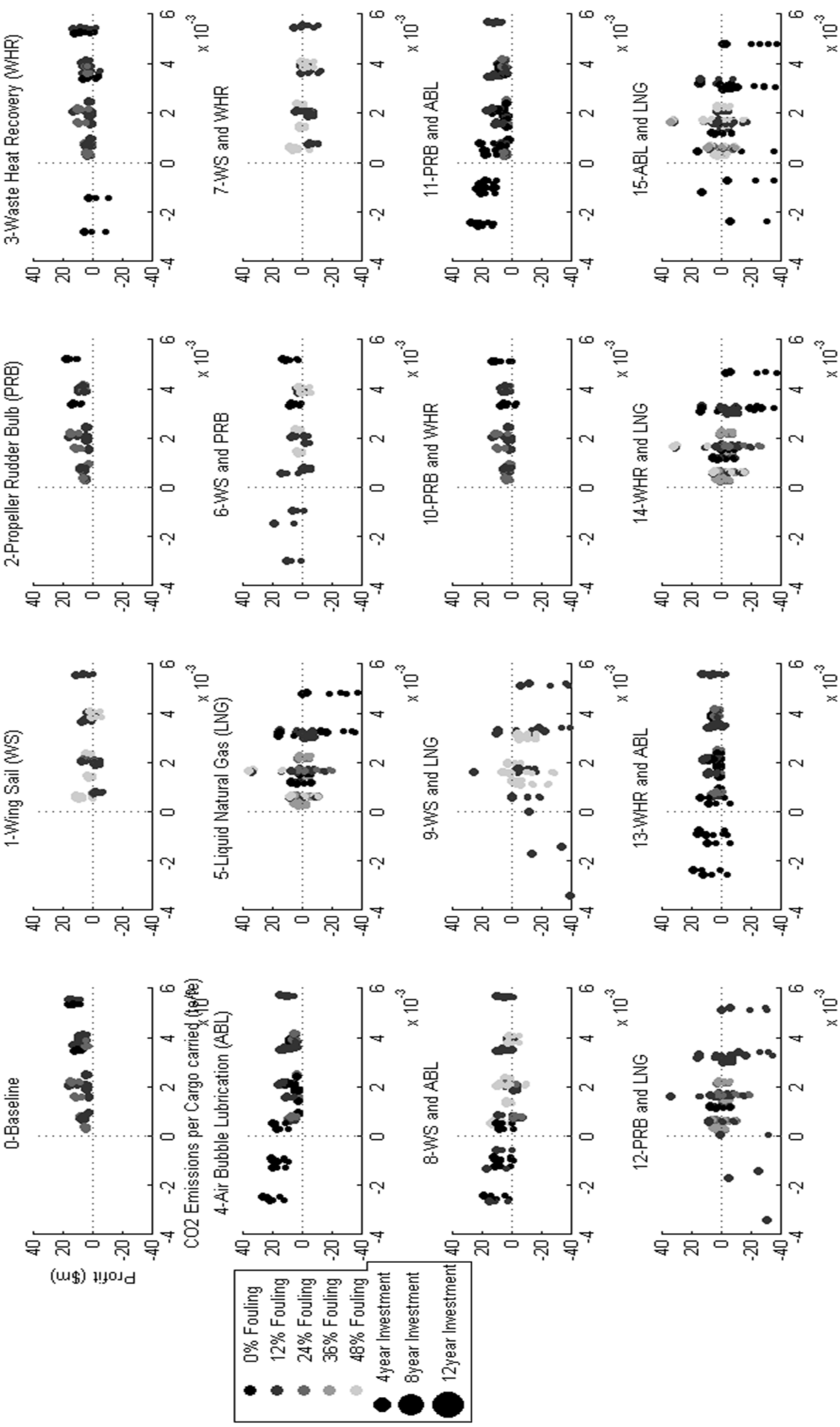
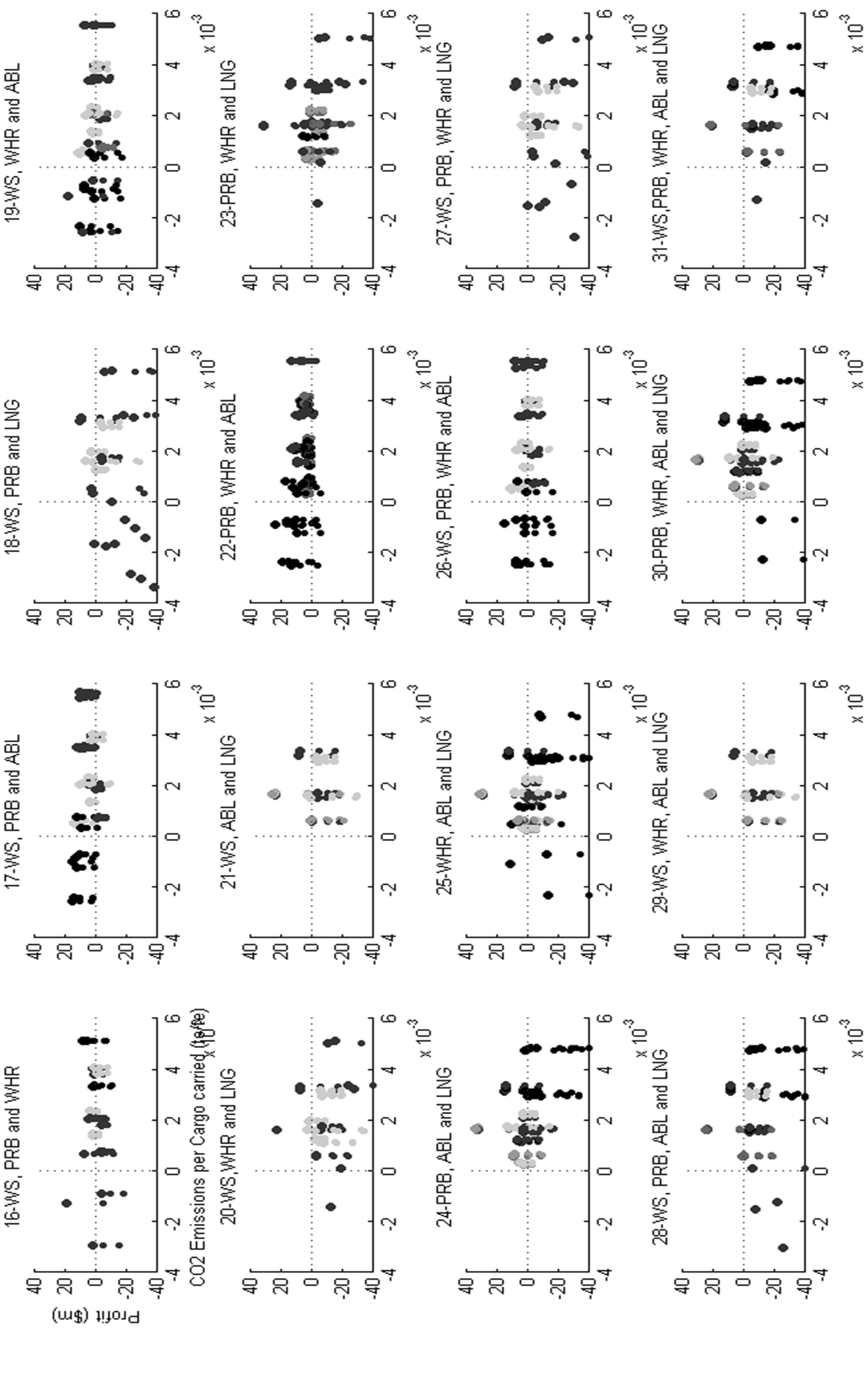



Figure 7.2: Additional profit against ratio of mass of $CO_2$ emissions to cargo for each CRT combination (change relative to a baseline ship) - the largest points represent an investment period of 12 years (two pages).


16-WS, PRB and WHR
17-WS, PRB and ABL
18-WS, PRB and LNG
19-WS, WHR and ABL
20-WS,WHR and LNG
21-WS, ABL and LNG
22-PRB, WHR and ABL
23-PRB, WHR and LNG
24-PRB, ABL and LNG
25-WHR, ABL and LNG
26-WS, PRB, WHR and ABL
27-WS, PRB, WHR and LNG
28-WS, PRB, ABL and LNG
29-WS, WHR, ABL and LNG
30-PRB, WHR, ABL and LNG
31-WS,PRB, WHR, ABL and LNG
Profit ($m)
CO2 Emissions per Cargo carried (te/te)

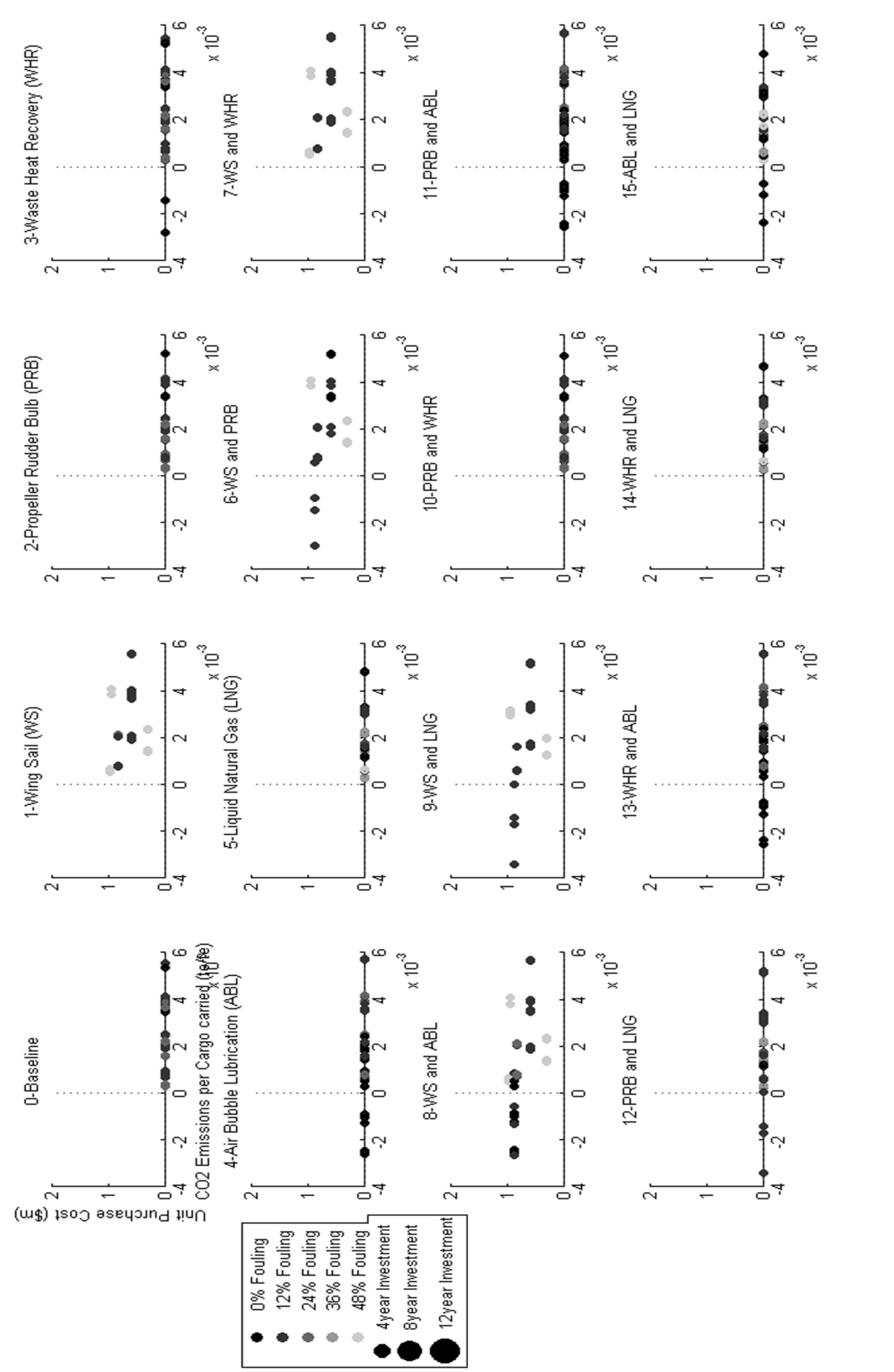
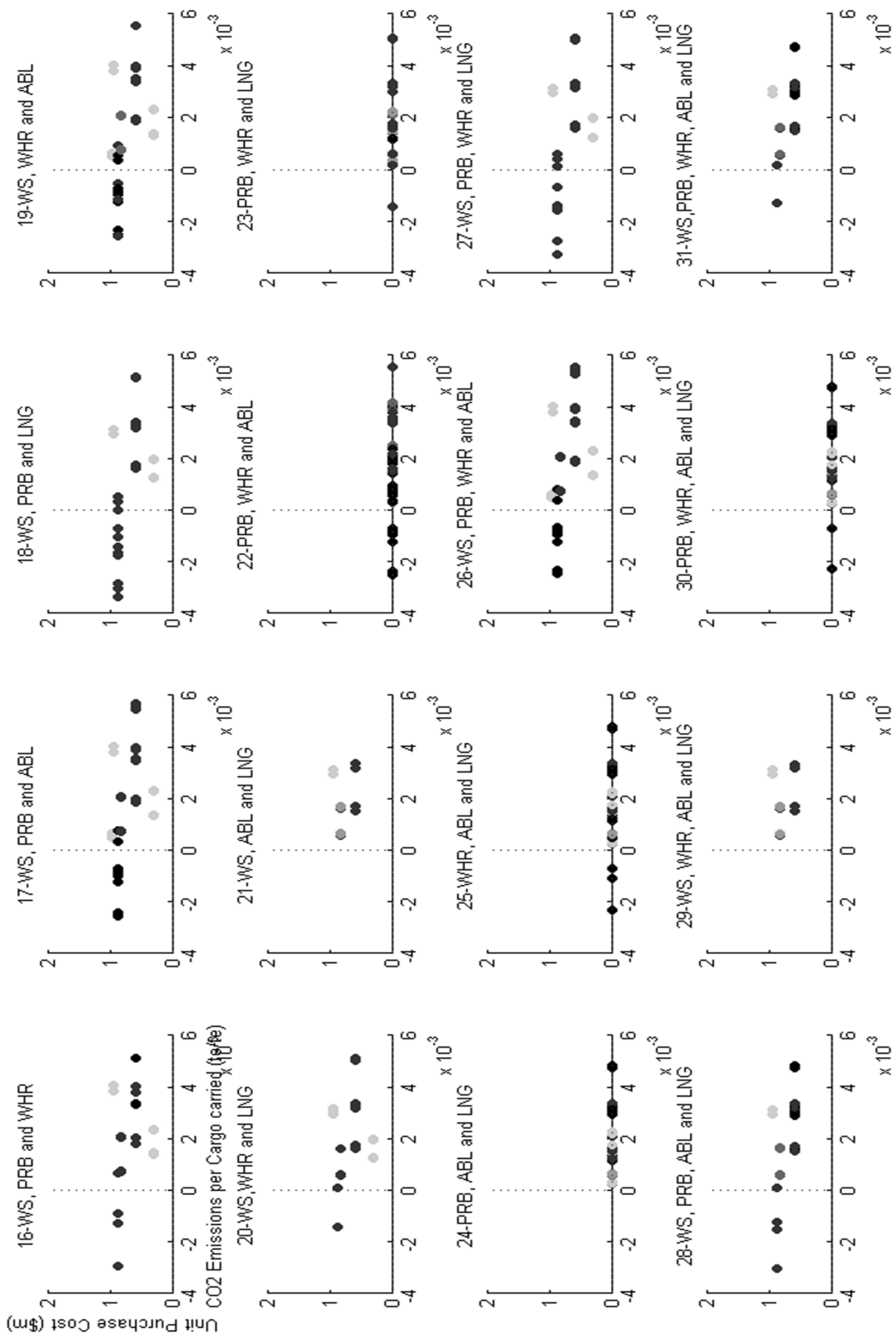



Figure 7.3: Additional UPC against ratio of mass of $CO_2$ emissions to cargo for each CRT combination (change relative to a baseline ship) - the largest points represent an investment period of 12 years (two pages).


16-WS, PRB and WHR
17-WS, PRB and ABL
18-WS, PRB and LNG
19-WS, WHR and ABL
20-WS,WHR and LNG
21-WS, ABL and LNG
22-PRB, WHR and ABL
23-PRB, WHR and LNG
24-PRB, ABL and LNG
25-WHR, ABL and LNG
26-WS, PRB, WHR and ABL
27-WS, PRB, WHR and LNG
28-WS, PRB, ABL and LNG
29-WS, WHR, ABL and LNG
30-PRB, WHR, ABL and LNG
31-WS,PRB, WHR, ABL and LNG
Unit Purchase Cost ($m)
CO2 Emissions per Cargo carried (te/te)
x 10^-3

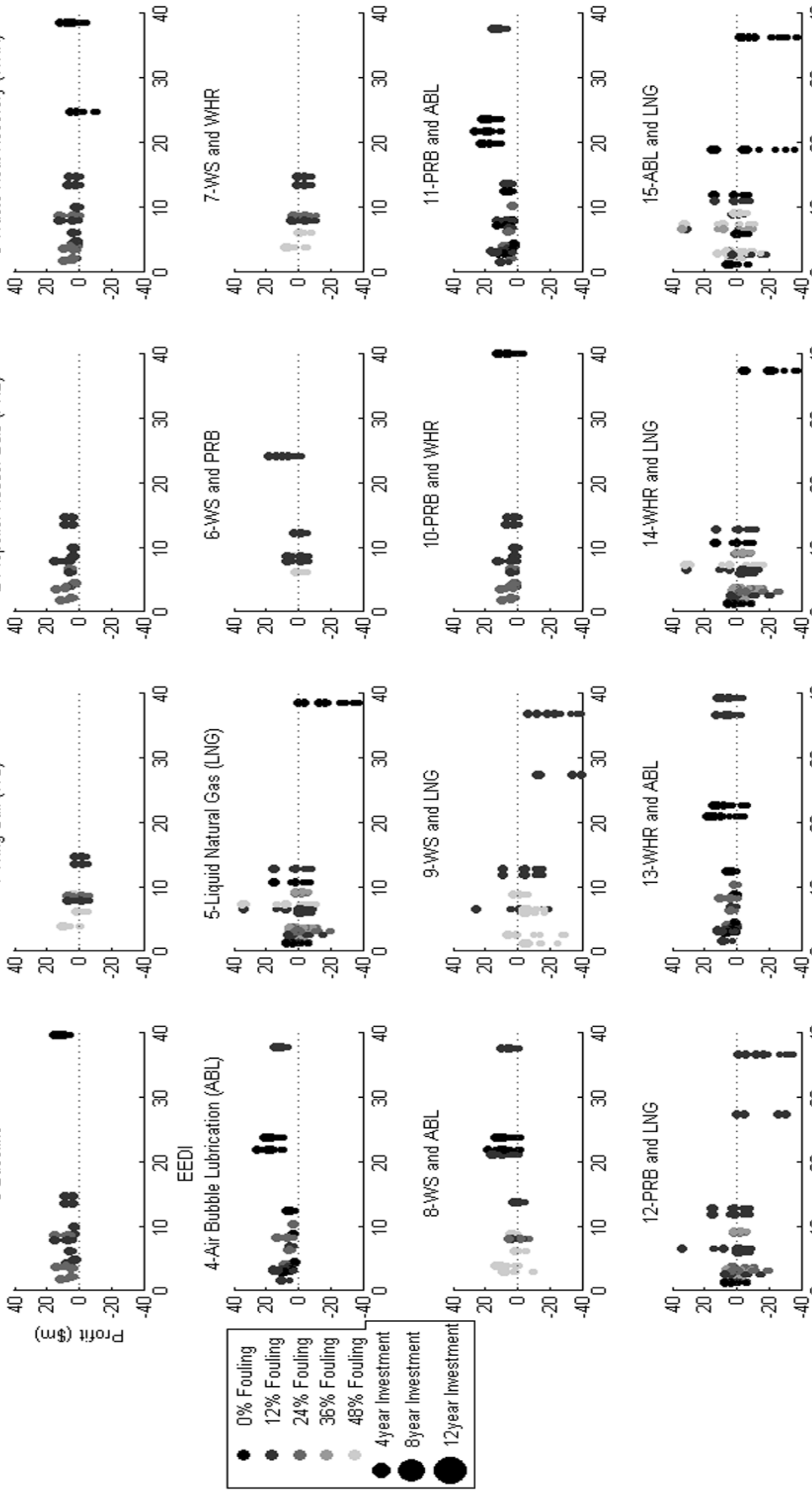
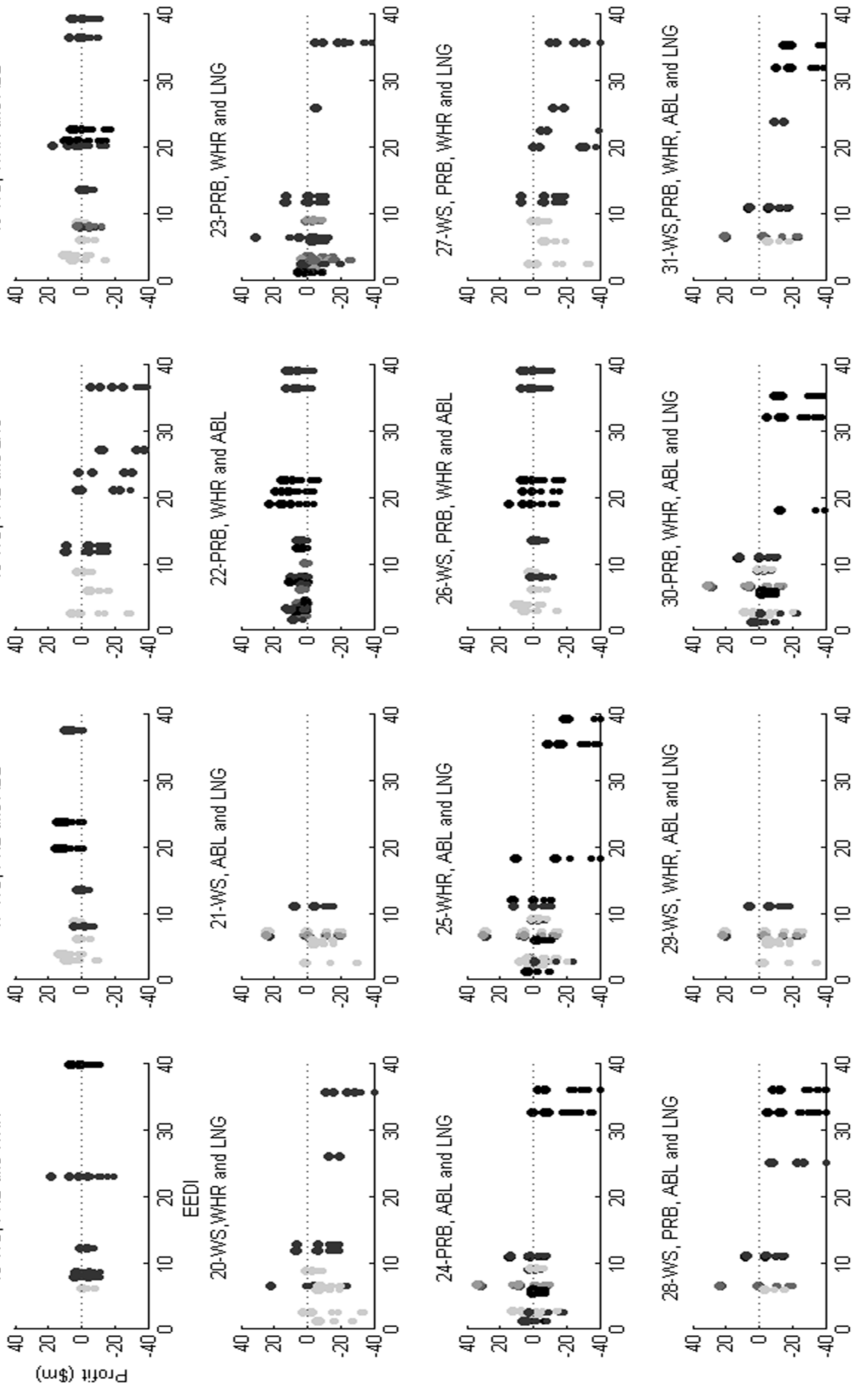



Figure 7.4: Additional profit against EEDI for each CRT combination (change relative to a baseline ship) - the largest points represent an investment period of 12 years (two pages).


16-WS, PRB and WHR
17-WS, PRB and ABL
18-WS, PRB and LNG
19-WS, WHR and ABL
20-WS,WHR and LNG
21-WS, ABL and LNG
22-PRB, WHR and ABL
23-PRB, WHR and LNG
24-PRB, ABL and LNG
25-WHR, ABL and LNG
26-WS, PRB, WHR and ABL
27-WS, PRB, WHR and LNG
28-WS, PRB, ABL and LNG
29-WS, WHR, ABL and LNG
30-PRB, WHR, ABL and LNG
31-WS,PRB, WHR, ABL and LNG
Profit ($m)
EEDI

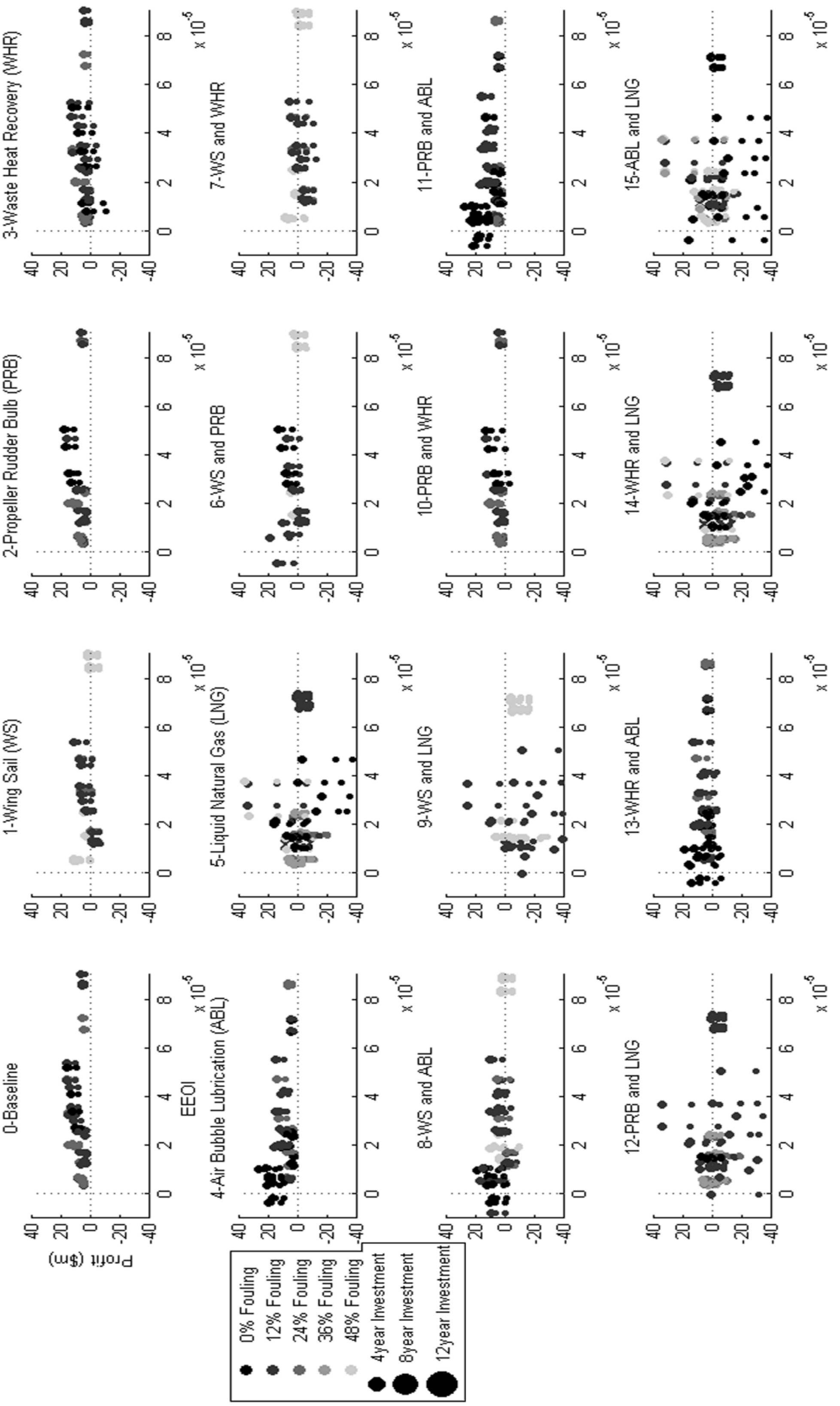
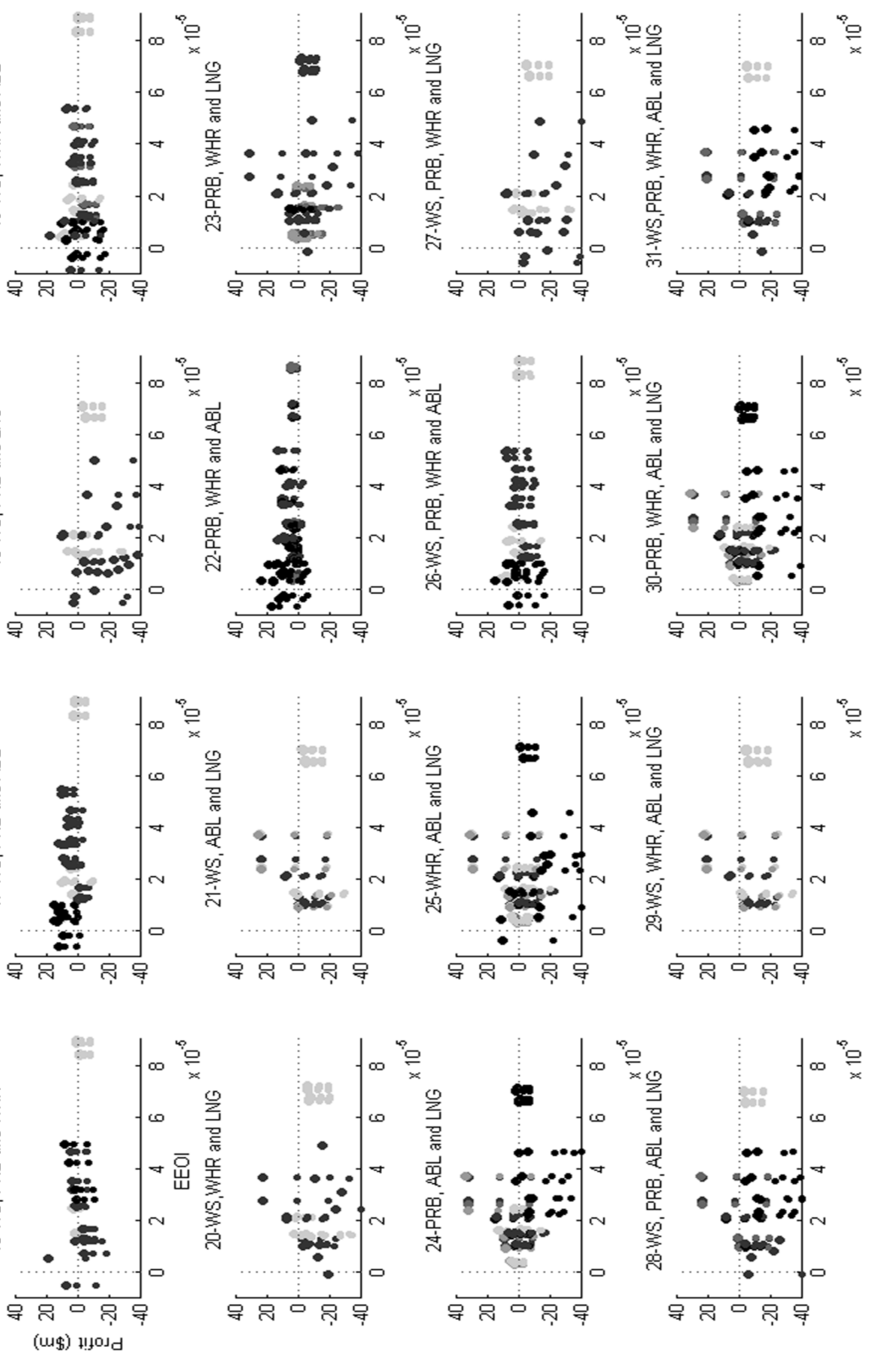



Figure 7.5: Additional profit against EEOI for each CRT combination (change relative to a baseline ship) - the largest points represent an investment period of 12 years (two pages).


16-WS, PRB and WHR
17-WS, PRB and ABL
18-WS, PRB and LNG
19-WS, WHR and ABL
20-WS,WHR and LNG
21-WS, ABL and LNG
22-PRB, WHR and ABL
23-PRB, WHR and LNG
24-PRB, ABL and LNG
25-WHR, ABL and LNG
26-WS, PRB, WHR and ABL
27-WS, PRB, WHR and LNG
28-WS, PRB, ABL and LNG
29-WS, WHR, ABL and LNG
30-PRB, WHR, ABL and LNG
31-WS,PRB, WHR, ABL and LNG
Profit ($m)
EEOI
x 10^-5

## 7.3 Observations on the Calculated Results

There are some limitations of presenting the data as shown in Figures 7.1, 7.2, 7.3, 7.4 and 7.5, as descussed in the previous Section. In order to make some further observations of the data without going through every individual ship design, the same data shown in the graphs in Section 7.2 was replotted, in Figures 7.6, 7.7, 7.8 and 7.9, to represent the results in terms of the number of CRTs fitted. In Figures 7.6, 7.7, 7.8 and 7.9 there are three columns of results above the number of CRTs, each representing a different investment period.

Some errors are likely to be present in the cost and profitability associated with the Propeller Rudder Bulb (PRB) due to the inaccuracies in the costing data, Unit Purchase Cost (UPC), for the Propeller Rudder Bulb (PRB) discussed in Subsection 7.1.1. Although the Propeller Rudder Bulb (PRB) likely represents the biggest source of error, in general, the costing data for all the technologies from LCS, in terms of Unit Purchase Cost (UPC) and Through-Life Cost (TLC), was difficult to carry out accurately and consistently. The other costs, not associated with the CRT, particularly fuel cost are consistent between different CRT combinations so the relative difference in profit between different CRT combination may be more accurate for longer investment periods, where UPC has less of a impact on profitability. Although fuel price is hard to predict. The profitability calculation assumes an oil and LNG price trajectory, the LNG price trajectory is pessimistic, especially compared to some other studies [Levander and Sipilä, 2008], to account for distribution and liquefaction costs.

When using Wing Sails and/or Air Lubrication, CRTs that affect the resistance (or thrust requirement) of a ship, heavily fouled ships, represented as light grey dots in Figures 7.1 and 7.2, have a larger percentage reduction in $CO_2$ emissions compared to lightly fouled ships, represented as black dots. This is because the different levels of fouling are represented as a percentage change from the baseline ship and for heavily fouled ships a higher proportion of a ships emissions will be associated with the skin-friction component of resistance. This means that CRTs that affect the skin-friction component of resistance will have a larger reduction in the percentage of $CO_2$ emissions compared to the baseline ship even though the total absolute $CO_2$ emissions of the ship have increased. Representing percentage reductions in this way can be misleading.

### 7.3.1 Profit and investment period

The longest investment period that was examined, 12 years, gives the highest potential profit, the longest investment period is represented by the biggest point size shown in Figures 7.6 and 7.7.

Figure 7.6 shows profit against the number of CRTs while Figure 7.7 shows the percentage change in profit against the number of CRTs.

The percentage change in profit is calculated relative to the baseline ship of the same size and cargo capacity in each case. This reduces uncertainty due to inaccuracies in the ship model and compensates for economies of scale, which would lead to larger ships being inherently more profitable.

For the maximum investment period that was examined, 12 years, fitting 1 to 5 of the selected 5 CRTs at once can be profitable. However, in order to maximise profit over a 12 year investment, fitting two CRTs

For the smaller investment periods, represented by the smaller circular points in Figures 7.6 and 7.7, an investment period of 8 years will allow for the fitting of one CRT to be profitable, while a 4 year investment period does not appear to be worthwhile. It also appears that the potential of making a loss also increases when more CRTs are used together, especially for smaller investment periods.

### 7.3.2 Percentage changes in ratio of mass of $CO_2$ emissions to cargo and percentage changes in the EEDI

It was necessary to divide the calculated $CO_2$ emisssions by the cargo to account for the change in cargo capacity due to a CRT. As mentioned earlier having the ratio of mass of $CO_2$ emissions to cargo as a non-dimensional ratio allows for comparison between ships and design and operational assumptions, this is also partly because the SIM works by calculating the impact of CRT combinations on cargo. Some measures of transport work (such as EEOI) account for speed or distance travelled. However, speed has a non-linear relationship with $CO_2$ emissions and both speed and distance travelled can vary depending on the specific ship that is being examined, so this may not help when comparing between different ship and CRT combinations.

In Figure 7.8, using a combination of more than three or four CRTs does not appear to provide any appreciable additional reduction in $CO_2$ emissions compared to using two or three CRTs.

This is because when increasing the number of CRTs used in combination and selecting the CRTs that have the biggest reduction in $CO_2$ emissions the more effective CRTs (in terms of highest reductions in $CO_2$ emissions) are taken up earlier so that when examing four or five CRTs used in combination the additional reduction in $CO_2$ emissions due to the additional CRTs is much smaller.

From Figure 7.9, the overall potential for reducing the percentage EEDI appears lower compared to the overall potential for reducing the percentage $CO_2$ emissions shown in Figure 7.8.

In Figures 7.8 and 7.9, all the investment periods (represented by different size dots) for the different combinations of ship and CRTs and design assumptions appear on top of each other so that only the largest dots can be seen. This is because the investment period effects the profit, which has not been plotted here, and has no effect on the $CO_2$ emissions or the EEDI.

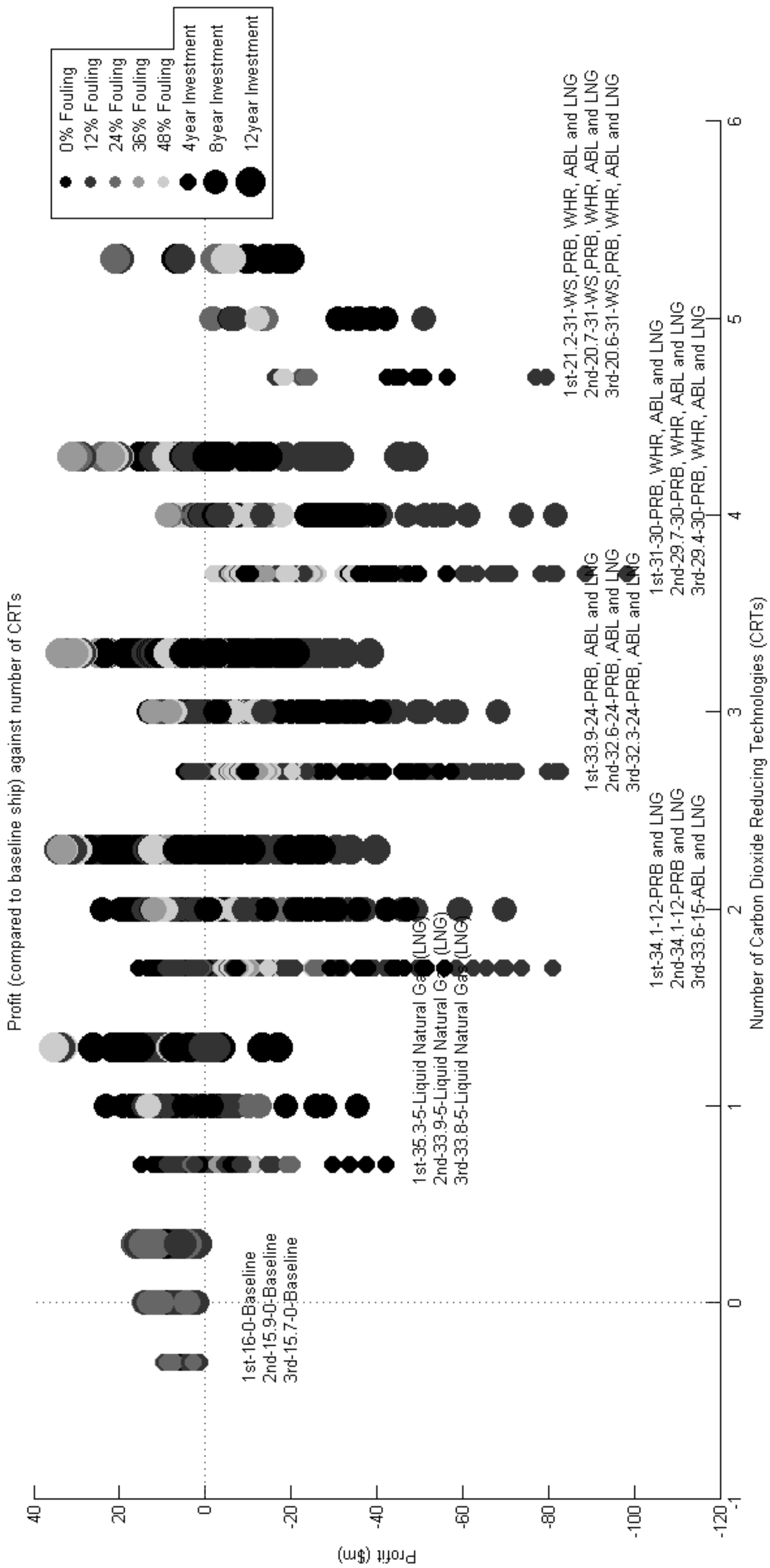



Figure 7.6: Change in profit ($m) compared to baseline ships against the number of CRTs used in combination.

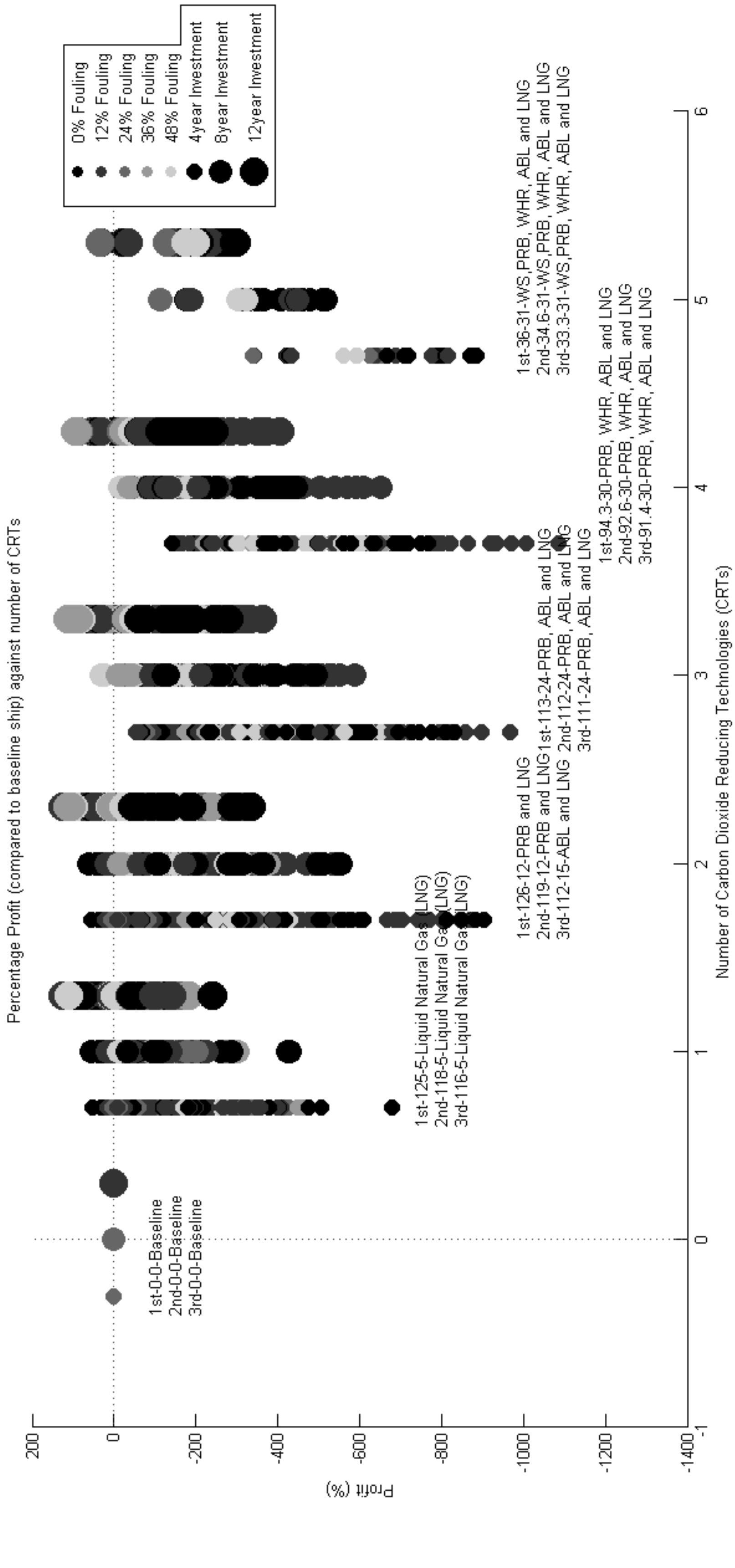



Figure 7.7: Percentage change in profit compared to baseline ships against the number of CRTs used in combination.

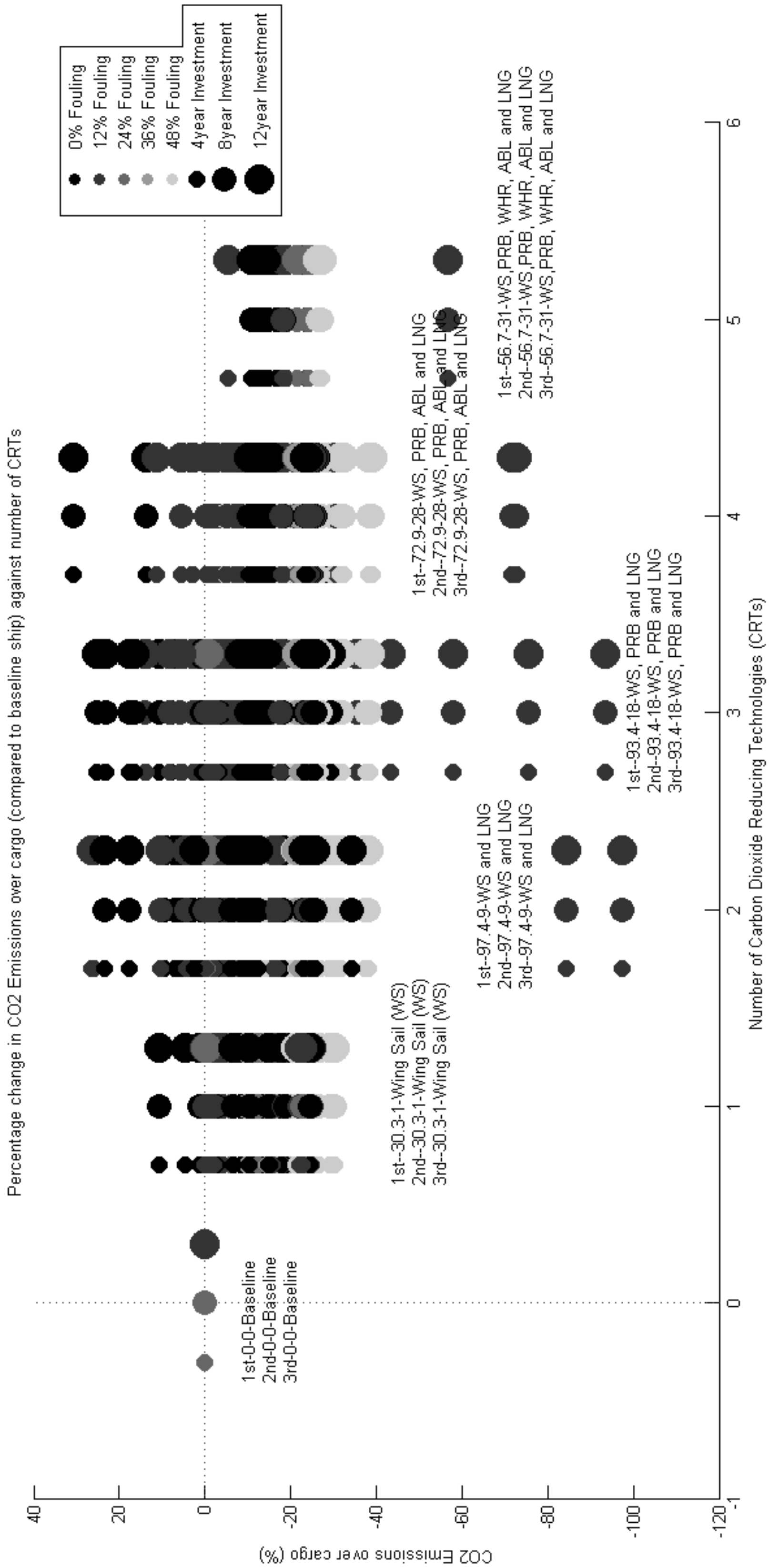



Figure 7.8: Percentage change in ratio of mass of $CO_2$ emissions to cargo compared to baseline ships against the number of CRTs used in combination.

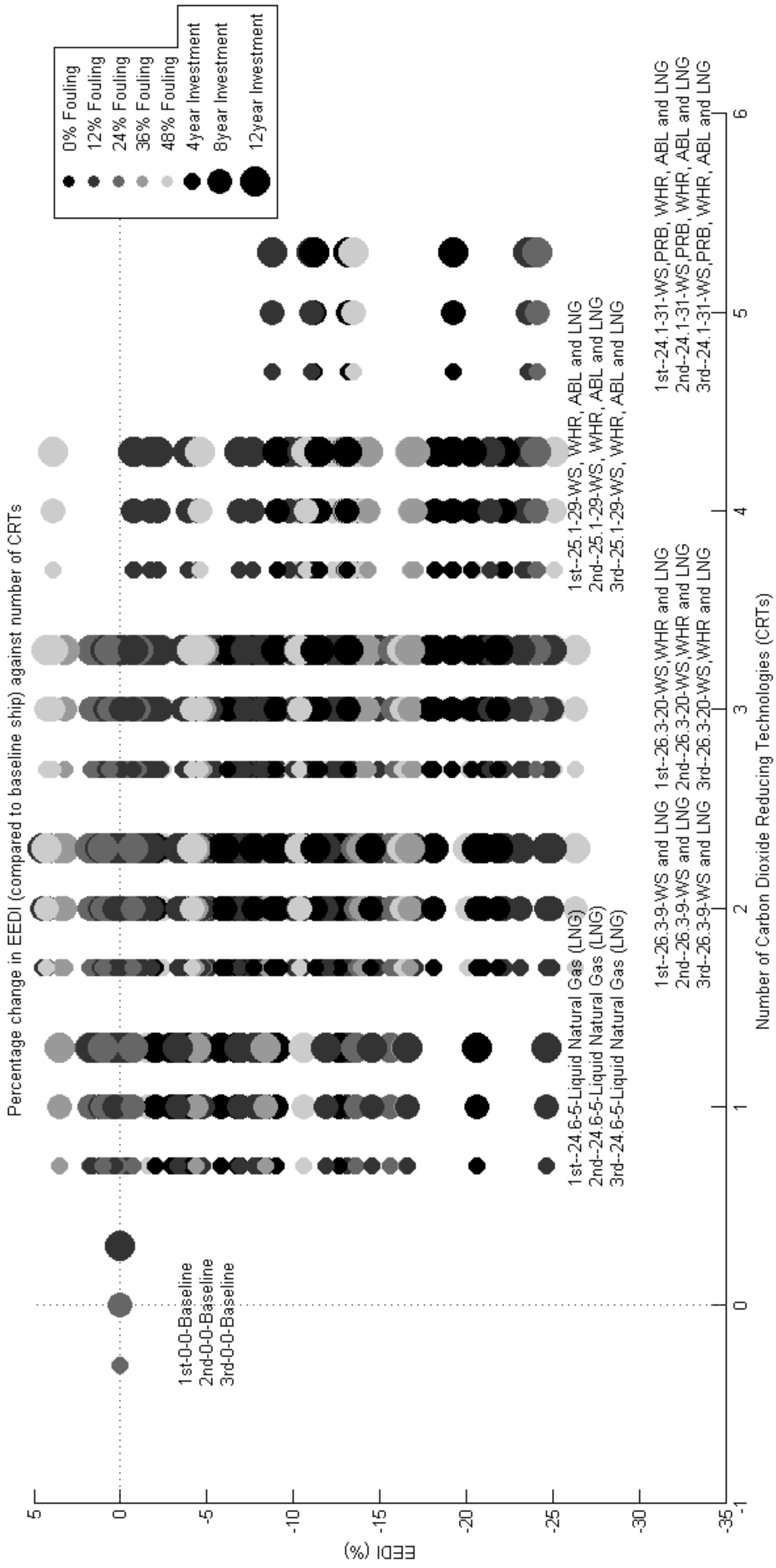



Figure 7.9: Percentage change in EEDI compared to baseline ships against the number of CRTs used in combination.

### 7.3.3 Comparison between maximising profit, minimising $CO_2$ emissions and minimising EEDI

Though CRTs will likely be selected by ship owners and ship operators mainly based on profitability, EEDI may provide some regulatory incentive to reduce $CO_2$ emissions. A comparison between the calculated profit maximum solution, the minimum $CO_2$ emissions solution and the minimum EEDI solution is shown in Table 7.4.

Table 7.4 uses the same data plotted in Figures 7.7, 7.8 and 7.9 to find the ships with maximum profit, minimum $CO_2$ emissions and minimum EEDI, respectively.

| Criteria | Number of CRTs | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Maximise Profit | Selected CRTs | LNG | **PRB & LNG** | PRB, ABL & LNG | PRB, WHR, ABL & LNG | All 5 CRTs |
| | Profit | 125.0% | **126.3%** | 113.3% | 94.3% | 36.0% |
| | $CO_2$/cargo | -21.6% | **-21.7%** | -21.3% | -21.4% | -21.5% |
| | EEDI | -24.6% | **-24.9%** | -17.1% | -17.1% | -24.1% |
| Minimise $CO_2$ emissions per cargo | Selected CRTs | WS | WS & LNG | WS, PRB & LNG | **WS, PRB, ABL & LNG** | All 5 CRTs |
| | Profit | -16.5% | -334.8% | -329.4% | **-307.0%** | -362.2% |
| | $CO_2$/cargo | -30.3% | -97.4% | -93.4% | **-72.9%** | -56.7% |
| | EEDI | -3.5% | 4.5% | 4.1% | **-4.5%** | -8.8% |
| Minimise EEDI | Selected CRTs | LNG | **WS & LNG** | WS, WHR & LNG | WS, WHR, ABL & LNG | All 5 CRTs |
| | Profit | -114.7% | **-239.9%** | -259.2% | -236.3% | -321.8% |
| | $CO_2$/cargo | -21.6% | **-30.7%** | -30.8% | -32.4% | -24.1% |
| | EEDI | -24.6% | **-26.3%** | -26.3% | -25.1% | -24.1% |

Table 7.4: Comparison between the Carbon Dioxide Reducing Technologies (CRTs) selected for different criteria; maximum profit, minimum $CO_2$ emissions and minimum EEDI for different numbers of CRTs.

The combination of CRTs that appear to have the highest profit and biggest $CO_2$ and EEDI reductions in Table 7.4 are represented in **bold** because the number and type of CRTs are different with each of these criteria. Five CRTs were compared and used in different combinations; Liquid Natural Gas (LNG), Wing Sails (WS), Propeller Rudder Bulb (PRB), Air Bubble Lubrication (ABL) and Waste Heat Recovery (WHR).

Depending on the investment period, fitting four or five CRTs quickly becomes too expensive to be able to make a profit over the investment period. All of the CRT combinations with the maximum profit that were selected, shown in Table 7.4 had the maximum possible investment period of 12 years.

For the large $CO_2$ emission reductions shown in Table 7.4 and Figure 7.8 the results are less clear, compared to profit. For two to five CRTs it appears that certain combinations of assumptions have led to very high and potentially unrealistic reductions in $CO_2$ emissions. The $CO_2$ emission reductions of 97.4% for two CRTs and 93.4% for three CRTs shown in Table 7.4 seem unrealistic because this high a reduction in $CO_2$ emissions does not seem possible compared to the initial $CO_2$ emission reductions for individual CRTs calculated for LCS in Section 6.2. It may be possible that the combination of Wing Sails (WS) with certain operating assumptions has led to very large reductions in $CO_2$ emissions. In Figure 7.8 these ships appear as dots on their own away from the majoritiy of the dots (or ships) suggesting that these savings are not possible for other ships and design and operational assumptions.

When finding the ships with the minimum $CO_2$ emissions and EEDI the investment period does not matter, the results at the minimum points that were selected automatically all had an 8 year investment period (although 4 and 12 year investment periods would give the same minimum $CO_2$ emissions and EEDI), this is why the CRTs, shown in Table 7.4 for minimising $CO_2$ and EEDI have a much lower profit compared to the CRTs for maximising profit. This can be seen in the results for maximising profit and minimising EEDI when using one CRT because the same CRT has been selected, but the calculated profit is different.

The general trend in Figure 7.8 appears to show that three or maybe four CRTs represent the biggest reduction in $CO_2$ emissions, although three CRTs have more spread in the results, so there may be less certainty and more risk. Although Figure 7.8 may also be showing the fact that for different combination of five CRTs the most combinations are possible for two and three CRTs. For example, when fitting four CRTs there are only five different CRT combinations from a selection of five CRTs.

For four CRTs, used in combination, a maximum $CO_2$ emission reduction of 72.9% was calculated, although it appears this is an extreme value and Figure 7.8 shows that the majority of the results are clustered around a $CO_2$ emission reduction of 40% to 50%, which may be more realistic. For the maximum reduction in $CO_2$ emissions for four CRTs was highlighed in **bold** in Table 7.4, rather than three CRTs, to emphasise the maximum possible reduction in $CO_2$ emissions that is likely from using more CRTs in combination.

As mentioned earlier in this section, when increasing the number of CRTs used in combination to get the maximum reduction in $CO_2$ emissions the more effective CRTs are used first so that the potential reduction in $CO_2$ emissions with each additional CRT reduces. However, interactions between the secondary effects of CRTs, particularly reducing the cargo capacity, will also reduce the calculated $CO_2$ emission reductions. This may explain the reducing $CO_2$ emission reductions when more CRTs are used in combination, particularly when using four or five CRTs, that appears to be shown in Table 7.4 and in Figure 7.8.

The higher calculated $CO_2$ emission reduction may be due to the maximum and minimum of different design and operation assumptions coming together to create a point that may be unrealistic for a real ship or a maybe an error, more likely in the input data rather than the model.

In Figures 7.1 and 7.2 many of the ships containing LNG are very expensive, with a large negative profit, the high UPC of LNG is shown in Figure 7.3. LNG can be expensive for many ships because these ships are likely to have a higher daily fuel consumption with large capacity LNG tanks and bigger engines and a shorter investment period. However, LNG was also used in the most profitable ship designs, as shown in Table 7.4, for a 12 year investment period. LNG also has a large reduction in EEDI and $CO_2$ emissions, compared to the other CRTs that were examined, making LNG a good option for some ships even when considering the pessimistic fuel price trajectory that was used.

In Table 7.4, wing-sails have a higher potential $CO_2$ emission reduction compared to LNG, this is consistent with the literature and the detailed analysis carried out outside the SIM in Sections 4.2 and 4.3, although for specific ships, where there is less available deck space for wing-sails, LNG may have a bigger $CO_2$ emission reduction than wing-sails.

Waste Heat Recovery (WHR) is not selected at all when using four CRTs to minimise $CO_2$ emissions because it is not as effective at lower main engine MCRs, however it is selected for minimising EEDI because EEDI is measured at the design MCR where Waste Heat Recovery (WHR) is likely to be the most effective. Propeller Rudder Bulbs (PRBs) work in the opposite sense and are effective over a speed range so that the resulting reduction in $CO_2$ emissions over an operating profile is enough for them to get selected, however the performance at one point is so small that they are not selected in order to minimise EEDI. Lastly it is also worth noting that Waste Heat Recovery (WHR) is only selected for EEDI and profit when considering four CRTs.

## 7.4 Summary and Conclusions

The number of valid ship and CRT combinations was 5232 compared to a total of 69120 combinations that were investigated, though this is not much of an issue because each individual combiation is quick to calculate. Valid ships being those that could reach their design speed and did not have too much installed power.

The rate on invalidty would in part be due to the input parameters being treated independently. For example, fouling is treated as a increase in skin-friction resistance that varied between 0% and 48%. A large increase in skin-friction resistance due to fouling combined with a low sea margin may result in a ship that cannot reach its design speed. Though, the linking of these assumptions may be iterative, especially when you consider that the addition of a CRTs can act to cause a ship design that was initially invalid, due to the input assumptions used on the baseline ship, to become a valid design.

Treating the input assumptions as independent variables and considering the ability to calculate the characteristics of lots of ships, CRTs and design combinations quickly has made it easier to populate a large design space. However, there are some unexpected results that could be due to a ship being designed for a unrealistic combination of input design and operation assumptions. It was expected that by running many combinations of assumptions it would be possible to find both the minimum and maximum profit, $CO_2$ emission reduction and EEDI. However it was only possible to find the CRT combinations with the maximum profit and minimum $CO_2$ emissions and EEDI because many ship and CRT combinations performed very badly, not giving a clear indication of the most realistic pessimistic design and operating scenarios for each CRT. This could be due to unrealistic input assumptions or maybe due to other errors in the input data or possibly from calculating ship characteristics that are outside the range of the data and equations used by the SIM. It may be difficult to determine if there are any sources of error here without having to examine each ship individually.

As mentioned at the beginning of Section 7.3, it was not possible to clearly show all the different ship design and operational assumptions for each CRT combination shown in the graphs in Section 7.2. From the graphs shown in Section 7.2, Figures 7.1, 7.2, 7.3, 7.4 and 7.5, the results of some CRT combinations appear to be distributed differently to others suggesting they are sensitive to different parameters. Some of these relationships are clearer in the Figures, such as in Figure 7.1 for both Propeller Rudder Bulbs (PRBs) and Waste Heat Recovery (WHR) the calculated points are close together suggesting they are fairly insensitive to changes in the added skin-friction resistance and likely most other design and operation assumptions that were examined too. There are many variables that can be individually explored to see what parameters different CRTs combinations are sensitive to.

Some of the calculated results were commensurate with those outlined by the literature review in Section 4.2 and Section 4.3 and Table 6.1. Though some of these results are clear and may not require such a detailed analysis they provide assurance that the SIM is giving meaningful outputs. The change in skin-friction resistance due to fouling had less of an impact on different CRTs combinations than was initially expected, particularly in terms of percentage changes, and some CRTs are more sensitive to this than others, with Wing-Sails (WS) in particular being the most effected.

There are some errors associated in the modelling of the CRTs. As discussed in Subsection 7.1.1, the data that was used from the LCS project describing the Propeller Rudder Bulb (PRB) is particularly uncertain. The other CRTs were easier to analyse with more certainty and the analysis of Liquid Natural Gas (LNG) and Wind is detailed in Section 4.2 and Section 4.3. Making comparisons to a baseline ship with no CRTs can assist in reducing errors in the ship description and the costs associated with the ship that are uneffected by CRTs, such as port and charter costs.

The maximum realistic $CO_2$ emission reductions from combinations of CRTs is around 40% to 50%, however in order to realise such benefits the investment period has to be longer than the 12 year maximum investment period that was examined here.

# Chapter 8

# Summary and Conclusions

## 8.1 Summary and Conclusion

In the previous Chapter it was examined how the output from the SIM could be used to explore a design space and select what CRT combinations are likely to be the best in terms of the highest profit and the lowest $CO_2$ emissions and EEDI with uncertain parameters. However, as discussed in Section 6.4, there are many other aspects that a ship owner or operator would need to consider. Presenting all the calculated data as shown in Section 7.2 with a separate graph for each CRT combination would be more useful (as different combinations are mutually exclusive and have to be calculated in the SIM, if possible, as mentioned in Section 6.3). This is because it allows a ship owner or operator to examine only those CRT combinations they are interested in, considering factors less amenable to quantification, such as depending on the ship owner or operators perception of risk and the resources and infrastructure that are available to them.

When selecting combinations of CRTs with the highest profit, Waste Heat Recovery (WHR) was not chosen until four CRTs are used. However, this is one of the more widely used CRTs on larger ships. This may be partly due to the performance of a Waste Heat Recovery (WHR) plant being easier to predict and hence less risky compared to CRTs which reduce resistance or improving propulsion efficiency, such as Air Bubble Lubrication (ABL). How the risks associated with WHR and other CRTs are perceived by ship owners or operators is important. Possibly how CRTs, such as WHR, are marketed is also a factor to consider. This illustrates that decisions are not purely economic as WHR may have been selected over more profitable CRTs.

The design methods employed with the SIM have been verified by comparing the results with conventional design methods, detailed in design studies in Section 4.2 and 4.3, comparing against a small amount of operational data and by validating against the initial literature review, summarised in Table 6.1. It has also been shown that the design and operation assumptions are very important, if not as important, as the CRTs themselves because the performance of different CRTs can vary considerably depending on the input assumptions. Maximum $CO_2$ reductions from combinations of CRTs being around 40% to 50%. In the general case, using two CRTs will definetely provide some benefits, while keeping risk low, three CRTs can also increase profit but the benefit in terms of both increasing profit, as an incentive, and reducing $CO_2$ emissions decreases as more CRTs are used in combination, a long investment period (longer than the 12 year maximum that was examined here) may allow combinations of four or five CRTs to be profitable.

The required long investment period is problematic because it increases risk as legislative demand for products, goods and raw materials can change. It is necessary to make the best estimate for the shipping capacity, but no one can be sure of the future [Stopford, 2009]. The risk of investing in CRTs for a particular ship may be coupled to the conventional risks in shipping. Several risks have to be considered when weighing up a shipping transaction, from the unpredictable market cycles, competition and the financial stability of companies to the risks associated with the operation and design of the ship itself [Stopford, 2009]. Risk is also far more devolved than in other industries, such as aviation.

Regarding the necessity to reduce $CO_2$ emissions, mentioned in Section 2.3, the main conclusions that can be drawn for modelling ship and CRT combinations have been split into three differerent categories; ship specific modelling considerations, broader shipping system modelling considerations and considerations for reducing $CO_2$ emissions from shipping.

Ship specific modelling considerations:

1. Operational CRMs and operational and design parameters, such as operating speed profile and cleaning and maintenance, are important operational assumptions for CRTs. Performance (in terms of profitability and $CO_2$ emissions) can vary greatly with operational and design assumptions and are as important as CRTs themselves especially when $CO_2$ emission reductions are small.

2. Operational feedback and detailed dissemination of detailed design data is important to improve modelling and validation (data for validating models is limited, as discussed in Section 5.8).

3. Combinations of CRTs that interact indirectly can be modelled.

4. It is unclear whether hydrodynamic and propulsor related CRTs can be scaled accurately (to different ship types, sizes and speeds) and some combinations of hydrodynamic and propulsor related CRTs cannot be calculated from independent performance information because they interact with each other directly and have to be modelled or tested together.

Broader shipping system modelling considerations:

1. There are qualitative barriers to selecting CRTs that could be based on opinion and/or risk. Some CRTs are better suited to some ships than others - it is better to present the performance for the full range of options and leave the qualitative selection criteria to the ship owner or operator.

2. The calculation of net present value, or a similar measure (such as required freight rate) is required to evaluate ship design and CRT options by considering both cost and operational performance.

3. The boundary for the shipping system is important. Changing the shipping system boundary can have a large effect on the results, sometimes it is also necessary to step outside the defined boundary to find out what needs to be included in the analysis and to calculate secondary effects at the boundary, for example a more fuel efficient ship also has the secondary effect of having a higher charter rate.

Considerations for reducing $CO_2$ emissions from shipping:

1. Increasing profit is the main incentive to use CRMs.

2. Long-term solutions, particularly changes in fuel infrastructure, are important for larger reductions in $CO_2$ emissions by enabling the wider adoption of certain CRTs.

3. Investment periods have to be very long, around 20 years - comparable to the life of a ship, to incentivise CRTs from increasing profit.

*The findings from Chapter 6 and Chapter 7, summarised in Section 6.6 and Section 7.4, were added to update this list from the findings in previous Sections (Section 2.8, Section 4.5 and Section 5.8) that were represented in a single list in chronological order (as they were discussed).*

These findings were made within the assumed shipping system boundaries detailed in Section 1.2, and under current regulatory framework described in Section 2.4.2.

### 8.1.1 Profit or the EEDI as an incentive to reduce $CO_2$ emissions

Maximising profit is likely to be the main incentive for adopting particular combinations of CRTs and the solution may be different from the combination of CRTs that will minimise $CO_2$ emissions or the EEDI. Increasing the profitability of a ship may in some cases also lead to a decision as to whether to use a CRT or not. For example, having a larger ship may be an alternative to LNG that may give a similar profit increase. There are two main differences between using profit or the EEDI as incentives to adopt CRTs:

- Profit can account for operational performance the EEDI does not.
- Profit ignores large $CO_2$ emission reductions completely if they are too expensive, especially for shorter investment periods.

The EEDI could force ship owners to go for more expensive Carbon Dioxide Reducing Measures (CRMs) that produce similar $CO_2$ emissions to less expensive Carbon Dioxide Reducing Measures (CRMs). However, for some CRTs using proft or EEDI as an incentive causes similar CRTs to be selected, especially for long investment periods. This was seen in Table 7.4 where for one CRTs Liquid Natural Gas (LNG) was found to be the best option to both maximise profit and minimise the EEDI.

The EEDI is more effective than profit for choosing what combinations of design and CRT parameters to select to reduce $CO_2$ emissions. Once a particular CRT combination has been selected, minimising $CO_2$ and EEDI and maximising profit are more likely to yield similar results. This means that diagrams for each CRT combination of profit against cost, like in a Marginal Abatement Cost Curve (MACC), can be represented as a rectangle, in general for a given CRT combination the maximum profit corresponds to minimum $CO_2$ emissions.

It can be argued that meeting legislation and tax regimes (such as Emission Control Area (ECA) and Market Based Measures (MBMs)) are all functions of fuel consumption, like profit, and therefore do not have to be considered independently from profit. The EEDI could be more useful if it was more biased towards the development of CRTs, to incentivise the use of CRTs, especially if they are not as profitable. Currently, when oil-based fuels are used the EEDI does not appear to provide any additional incentive to adopt CRTs that profit does not. Designing to increase profitability rather than regulation may be better because regulations can change and can be influenced by technology; profitable designs and CRT combinations are more likely to stay profitable.

### 8.1.2 Development of a new CRT selection tool

In Subsection 1.3.1 it was mentioned that the aim of this work is to: *"Develop a tool to provide quick and coherent early stage design guidance for the selection of multiple Carbon Dioxide Reducing Technologies (CRTs) that is robust to changing operational assumptions."*

The Ship Impact Model (SIM) was developed as a CRT selection tool and an early stage ship design tool by allowing a large design space to be explored quickly, incorporating economic considerations at a single ship level and supporting combinations of CRTs.

The SIM has been used in two projects (see Appendix A and Appendix B) as both an early stage design tool and potentionally to advise on regulation and what $CO_2$ emission reductions are possible from shipping (particularly with the existing fuel infrastructure).

Whilst considering that comparisons against actual ship data have been limited, the fidelity and accuracy of the SIM are both high enough to use the SIM as a decision tool in the selection between different CRT combinations. Validation of the results was carried out by comparing against ship data and the results produced by different models, particularly the Whole Ship Model (WSM), from which the SIM was initially developed by simplifying the design process carried out by the WSM. See Chapters 4 and Chapter 5 (particularly Section 5.6).

The main areas for improvement is the input data and in the CRTs descriptions from the LCS project, rather than the SIM itself. The CRT descriptions that were used for the LCS project contain some erroneous and low fidelity parameters, particularly in the description of the Propeller Rudder Bulb (PRB) and other (hydrodynamic) CRTs that affect the propulsion coefficient. This was initially discussed in Subsection 7.1.1. Future work, discussed in detail in the next Section, is also needed to further techniques for analysing and filtering the large amount of output data from the SIM. One of the unexpected outcomes was that in examining so many ship, CRT and input parameter combinations many of the ship designs that were produced by the SIM performed badly (in maximising profit as well as minimising $CO_2$ emissions and the EEDI). It may also be necessary to be more careful in the selection of the input design and operational parameters, possibly by considering dependencies between the input parameters.

## 8.2 Additional Considerations

There are some additional considerations that have not been studied because they are outside the scope of this work, defined in Section 1.2:

- Sale of vessel and second-hand market - also needed to examine retrofits. Some ship owners and operators will buy or charter newer ships with CRTs, however the less efficient ships displaced by newer ships may be sold cheaply on the second-hand market, so new ship designs may take some time to be taken up by the rest of the sector.
- Embedded $CO_2$ Emissions, such as $CO_2$ emissions in build and in the fuel infrastructure.
- Difference between a new build ship and retrofitting to existing ships - information about the CRT has to contain retrofit, as well as new build, performance and cost.
- Variables related to the CRTs and fuel were not examined, for example a sensitivity analysis for different fuel trajectories and CRT performance estimations could be carried out using the SIM, but for this work a pessimistic fuel trajectory for LNG from LCS was used.
- Alternative transport modes which may compete for some routes, such as rail and aviation can impose additional bounds on the cost and speed of ships - this is particularly important when considering the specification (and voyage) of new ships.
- The effect of possible future regulation, such as the effect of a carbon tax.

Looking at different regulatory scenarios could help to provide more guidance on how regulation should be applied and would allow for ship owners or operators to compare different scenarios in their examination of risk. Though looking at different regulatory scenarios may not provide additional guidance as to which specific CRT will be adopted over others as future regulation will likely be based on $CO_2$ emissions and as noted in Section 8.1, CRT selection is dominated by profit considerations rather than $CO_2$ emissions; both $CO_2$ emissions and profit have been considered in this Thesis.

Some parameters were not varied in the sensitivity analysis, though the Ship Impact Model (SIM) is capable of modelling these, these were mentioned in Subsection 7.1.5:

- Heat energy utilisation.
- Endurance/range - important consideration with operating profile when considering different fuels.

- Design speed of hull.
- Shaft generator - Power-Take-In (PTI) or Power-Take-Off (PTO).
- Controllable Pitch Propeller.

The design speed of hull is of particular interest for future work and was covered in the discussion of the capability of the SIM in Section 5.7 and is also mentioned in the following Subsection.

### 8.2.1 Designing for operating speed profiles and for flexibility

Two different operating speed profiles were examined with different ship design and operational assumptions and different CRTs in the sensitivity study. A conventional slow steaming operating speed profile and an operating speed profile with a narrower band of speeds (with no slow steaming). In some instances, such as on very large cargo ships with fixed routes or passenger ships, it may be possible to design the ship and operational speed profile in tandem for the best efficiency. “Virtual arrival” can be used (this was discussed in Subsection 2.6.5) to agree berthing times and hence voyage with all the parties involved. If the voyage time is set this allows a operating speed profile to be used that minimises fuel consumptions and maximises the benefits of CRTs.

Without “virtual arrival” ships may have to be designed for a high efficiency at a wider range of speeds; with “virtual arrival” ships can be designed to be efficient for a narrower range of speeds. This means that the speeds and the time spent at each speed can be planned, this may allow higher efficiencies due to a trade-off between flexibility and overall efficiency. Though there are some definite benefits to selecting the operating profile to work with certain ships, routes and CRTs this will make ships inflexible to the weather - in particular, as well as voyage routes and will benefit some CRTs, such as wind energy, more than others.

Section 5.7 demonstrated how the Ship Impact Model (SIM) could be used to set the design point of different components of a ship, the hull, engine and propeller, to improve the overall perfomance of the ship over an operating profile. The overall ship can be made to be more flexible, designed to operate at a high efficiency over a range of operating points, however more flexible systems usually come at a loss in efficiency at a single operating point.

## 8.3 Future Work

Uncertainty in the modelling and results should be quantified and addressed. If there were sufficient data available a probability distribution for each of the input variables could be used instead of fixed values. The SIM would be well suited to carrying out a Monte Carlo simulation using input parameters that are probablility distributions because the SIM can calculate the performance of lots of ships and CRT combinations quickly. This would allow for the possible variation and uncertainty in the performance (in terms of maximising profit and minimising $CO_2$ and the EEDI) of different ship and CRT combinations to be calculated. This should provide a better basis for making decisions about the risks in adopting certain CRTs, because the full range of possible outcomes can be taken into account.

The combination of mathematical and spatial models in the SIM and the WSMs, respectively, has helped to fill in many gaps in the available data. More detailed data that is taken from one place (for example, measuring draught and speed from the same ship at the same time) would give more about how different parameters in the system are related and how ships are operated and how their performance can deteriorate, such as through wear and fouling. It would also be necessary to have information on different voyages and ship types to cover a sufficient range of possible ships and operating scenarios and not just one particular ship and/or voyage. All of this would help Naval Architects and Marine Engineers to design ships for better operational performance.

Considering that the design and operation assumptions are both important and can be uncertain; future work should include:

- More emphasis on modelling and designing systems to represent synergistic combinations of technologies - such as hybrid arrangements and PTIs and PTOs.
- Improvements to CRTs description; to better describe the variations in their performance with changing design parameters and operational conditions (this will assist creating a better model to examine operational flexibility).
- More emphasis on operational flexibility considering operational speed profiles and the environment (such as weather and ambient conditions).
- A probabilistic approach can be used to quantify possible variations and uncertainty in the performance (in terms of maximising profit and minimising $CO_2$ and the EEDI) of different CRTs.

In particular, as mentioned in Subsection 6.2.3, hydrodynamic and propulsor related CRTs that normally effect propulsion efficiency or resistance, such as Propeller Rudder Bulbs (PRBs), ducts, and pre-swirl and post-swirl devices, can be difficult to model because they operate in the complex flow around the ship.

Adding extra fidelity to the SIM or linking the SIM to more detailed models, meta-models or response surfaces that descibe specific parts of the ship in high detail could achieve the above aims for future work. It may also be necessary to consider, if it is possible to add detail in this way, more time domain analysis of the environment (such as weather and ambient conditions). This would also help to develop research in the implementation of wind energy on ships, that has high potential for reducing $CO_2$ emissions from shipping.

The Ship Impact Model (SIM) is able to produce a wide range of outputs describing how energy is used depending on the input decision variables. An interactive energy flow and ship performance diagram illustrating what type of energy is being used where in the ship, may allow the examination of:

- Data in lots of dimensions (not all information can be displayed at once).
- The effect of changing decision variables on the performance of the ship.

This may be similar to using interactive Sankey diagrams to explore complex flow scenarios [Riehmann et al., 2005]. This could be carried out by pre-calculating a large database of results and then analysing them afterwards, as has been done in this thesis or by by a mixture of pre-calculation and direct calculation. Visualising what type of energy is being used where would be of use in designing better ship systems, individual components and reducing conversion losses.

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## Appendix A

# About Low Carbon Shipping - A Systems Approach

## A.1 Introduction to Low Carbon Shipping (LCS)

This section details how the ship modelling and the Ship Impact Model were used in the "Low Carbon Shipping  A Systems Approach" (LCS) project and provides some additional results. Two papers overlap heavily with the brief LCS project summary given here and should be consulted for further information. The initial paper was in 2010 and was a introduction to the project [Smith et al., 2010] and, more recently a paper that served as a update in 2012 [Calleya et al., 2012]; this was also rewritten for the Naval Architect in January 2013.

The RCUK Energy funded research project "Low Carbon Shipping: A Systems Approach" (LCS) started in 2010. The projects aim is to use understanding of the many components of the shipping system to explore how the shipping industry might respond to the challenge of a GHG constrained future e.g. from a combination of the technological, economic, logistical, operational and infrastructure perspectives.

LCS is a multidisciplinary investigation of the transport system, considering:

- Transport logistics.
- Future ship designs.
- Demand for shipping and trade flows.
- Technical and policy solutions.
- Implementation barriers.
- Measurement and apportionment.

LCS was majority funded by the RCUK energy programme (initially £1.7m over 3 years), the grant reference is EP/H020012/1, and consists of five UK universities (Plymouth, Newcastle, Hull, UCL and Strathclyde) and supported by maritime organisations:

- Lloyd's Register
- The Royal Institution of Naval Architects
- The British Chamber of Shipping
- Atkins
- QinetiQ
- Fisher
- James Fisher and Sons
- Shell
- Rolls Royce
- World Wide Fund for Nature (WWF)
- BP
- Ministry of Defence
- The United Kingdom Major Ports Group Limited (UKMPG)
- BMT Group
- Lloyds Register Fairplay
- Caledonian Macbrayne

Low Carbon Shipping (LCS) focuses on international shipping through the examination of the four major ship types (container ships, bulk carriers, oil tankers and LNG tankers) that are expected to emit the greatest amount of CO2 in the next 40 years. The LCS project is split into six work packages, as shown in Figure A.1, with UCL Naval Architecture and Marine Engineering (NAME) is part of Work Package 2: Technologies focussing on capturing the technology impact on ships.

There were three key aims for Work Package 2: Technologies:

- Explore technical solutions.

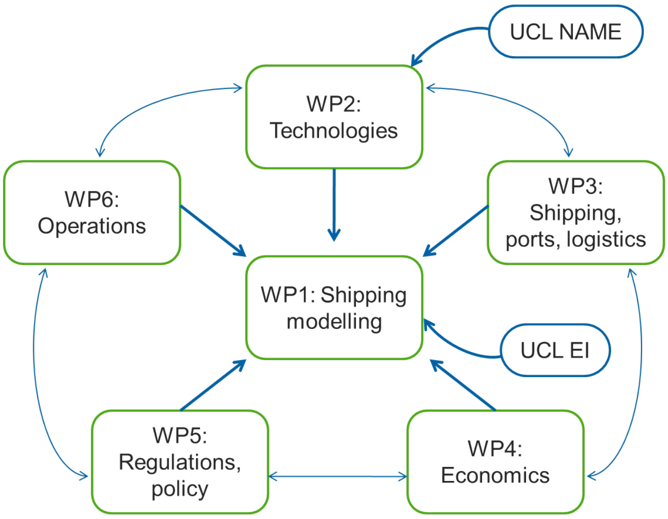


Figure A.1: LCS Project Structure and Work Packages [Pawling, 2011].

- Identify areas for $CO_2$ emissions reduction.
- Provide input in the shipping system model.

Figure A.2 shows how the ship modelling in Work Package 2 works with the rest of Work Package 2 and the other Work Packages and how data is passed onto Work Package 1 for use in the shipping system model. Detailed engineering solutions for different low $CO_2$ technologies are investigated by engineers in Work Package (WP) 2 and Logistical, Costing and Operational constraints are investigated in Work Packages (WP) 3-6, this information is then captured in the ship designs, which are used to estimate the $CO_2$ emission reductions and cost for different ship types, sizes, speeds and $CO_2$ reducing technologies. The economic model can then select the most appropriate technologies according to market conditions and regulatory constraints, rather than based on engineering decisions.

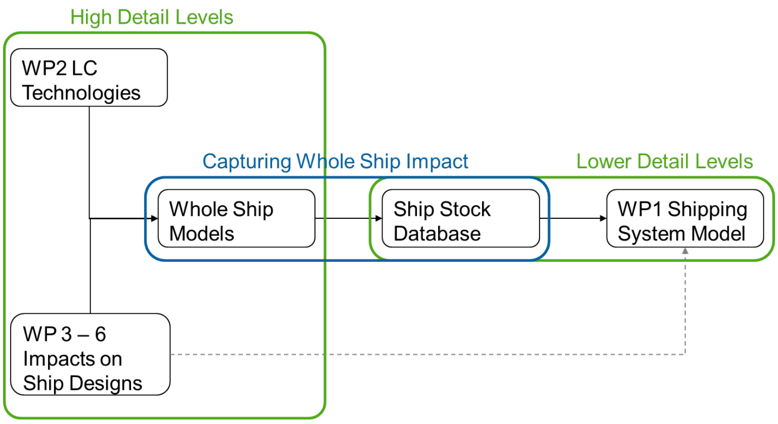


Figure A.2: Input into Shipping System Model [Dr. R. Pawling, 2011].

The economic analysis from the shipping system model can help to develop a better understanding of the most likely future ship designs and technologies.

## A.2 Detailed outputs from the Ship Impact Model for LCS

Tables A.1, A.2 and A.3 compare the performance of the full list of technology options, Carbon Dioxide Reducing Technologies (CRTs), that were investigated in Low Carbon Shipping (LCS). In section 6.2 only the options, CRTs, that were the most accurate and analysed in detail and the most likely to be adopted were taken from the outputs shown in Tables A.1, A.2 and A.3.

| Carbon Dioxide Reducing Technology (CRT) | Calculated EEDI | $CO_2$ emissions | $CO_2$ emissions over cargo |
|---|---|---|---|
| Baseline ship | 35.35 | 0.0% | 0.0% |
| Superstructure streamlining | 35.35 | -0.1% | -0.1% |
| Wing pods | 31.42 | -4.9% | -6.2% |
| Pulling pods | 31.65 | -4.9% | -5.5% |
| Contra-rotating propeller | 35.46 | -2.0% | -0.7% |
| Vane wheel | 33.83 | -0.5% | -0.3% |
| Propeller section optimisation | 35.12 | -1.3% | -1.3% |
| Ducted propellers | 40.41 | 6.0% | 9.3% |
| Pre-swirl duct | 35.19 | -1.1% | -1.0% |
| Propeller upgrade | 35.13 | -1.3% | -1.3% |
| Propeller boss cap fins | 35.13 | -1.3% | -1.3% |
| Asymmetric rudder | 35.24 | -0.7% | -0.7% |
| Propeller rudder bulb | 35.24 | -0.7% | -0.7% |
| Waste heat recovery | 34.41 | 0.1% | -0.1% |
| Air bubble lubrication | 34.85 | -4.8% | -4.4% |
| Air cavity lubrication | 35.10 | -3.5% | -2.9% |
| Hull coatings | 30.91 | -5.4% | -8.1% |
| Hull maintenance | 35.28 | -0.5% | -0.5% |
| Regular propeller polishing | 35.12 | -1.3% | -1.3% |
| Liquid Natural Gas for auxiliary power | 35.07 | -7.3% | -6.0% |
| Liquid Natural Gas for main engine | 35.35 | -9.3% | -0.6% |
| Liquid Natural Gas for both | 34.91 | -16.6% | -7.5% |
| Soft sails | 35.06 | -4.7% | -4.0% |
| Wind engine | 35.69 | 0.0% | 1.0% |
| Kite | 35.35 | -0.1% | -0.1% |
| Optimise flow over openings | 35.34 | -0.1% | -0.1% |
| Covering hull openings | 35.26 | -0.6% | -0.6% |
| Variable speed pumps and fans | 35.30 | 0.0% | 0.0% |
| LED lighting | 35.35 | 0.0% | 0.0% |
| Optimisation of dimensions | 30.30 | -9.4% | -11.3% |
| LNG Fuel Cell for auxiliary power | 35.23 | -7.3% | -5.0% |
| Main engine tuning | 33.37 | -9.2% | -8.4% |
| Photovoltaic solar cells | 35.34 | 0.0% | 0.0% |

Table A.1: Output results from the SIM for LCS for a 35 000 tonne deadweight 25 knot Panamax container ship calculated using the operating assumptions detailed in Section 5.3.

| Carbon Dioxide Reducing Technology (CRT) | Calculated EEDI | $CO_2$ emissions | $CO_2$ emissions over cargo |
|---|---|---|---|
| Baseline ship | 6.48 | 0.0% | 0.0% |
| Superstructure streamlining | 6.48 | -0.1% | -0.1% |
| Wing pods | 5.70 | -3.2% | -3.5% |
| Pulling pods | 5.71 | -3.2% | -3.4% |
| Contra-rotating propeller | 6.43 | -1.4% | -1.2% |
| Vane wheel | 6.21 | -1.1% | -1.1% |
| Propeller section optimisation | 6.44 | -0.9% | -0.9% |
| Ducted propellers | 6.43 | -2.3% | -2.3% |
| Pre-swirl duct | 6.42 | -1.5% | -1.4% |
| Propeller upgrade | 6.44 | -0.9% | -0.9% |
| Propeller boss cap fins | 6.44 | -0.9% | -0.9% |
| Asymmetric rudder | 6.46 | -0.5% | -0.5% |
| Propeller rudder bulb | 6.46 | -0.5% | -0.5% |
| Waste heat recovery | 6.48 | -0.8% | -0.8% |
| Air bubble lubrication | 6.39 | -3.8% | -3.7% |
| Air cavity lubrication | 6.43 | -3.1% | -3.0% |
| Hull coatings | 6.33 | -3.0% | -3.0% |
| Hull maintenance | 6.45 | -0.7% | -0.7% |
| Regular propeller polishing | 6.44 | -0.9% | -0.9% |
| Liquid Natural Gas for auxiliary power | 6.25 | -13.6% | -13.3% |
| Liquid Natural Gas for main engine | 6.54 | -3.5% | -0.9% |
| Liquid Natural Gas for both | 6.27 | -17.1% | -14.7% |
| Soft sails | 6.37 | -4.9% | -4.5% |
| Wind engine | 6.51 | -0.0% | 0.5% |
| Kite | 6.48 | -0.7% | -0.7% |
| Optimise flow over openings | 6.48 | -0.1% | -0.1% |
| Covering hull openings | 6.46 | -0.4% | -0.4% |
| Variable speed pumps and fans | 6.42 | 0.0% | 0.0% |
| LED lighting | 6.48 | 0.0% | 0.0% |
| Optimisation of dimensions | 6.42 | -2.6% | -1.8% |
| LNG Fuel Cell for auxiliary power | 6.04 | -12.2% | -11.7% |
| Main engine tuning | 6.11 | -6.5% | -6.3% |
| Photovoltaic solar cells | 6.25 | -3.7% | -3.7% |

Table A.2: Output results from the SIM for LCS for a 55 000 tonne deadweight 15 knot Panamax bulk carrier calculated using the operating assumptions detailed in Section 5.3.

| Carbon Dioxide Reducing Technology (CRT) | Calculated EEDI | $CO_2$ emissions | $CO_2$ emissions over cargo |
|---|---|---|---|
| Baseline ship | 6.00 | 0.0% | 0.0% |
| Superstructure streamlining | 6.00 | 0.0% | 0.0% |
| Wing pods | 5.81 | -1.8% | -1.5% |
| Pulling pods | 5.82 | -1.8% | -1.4% |
| Contra-rotating propeller | 5.94 | -0.7% | -0.5% |
| Vane wheel | 5.73 | -1.4% | -1.3% |
| Propeller section optimisation | 5.95 | -0.4% | -0.4% |
| Ducted propellers | 5.93 | -1.1% | -1.1% |
| Pre-swirl duct | 5.92 | -0.7% | -0.7% |
| Propeller upgrade | 5.95 | -0.4% | -0.4% |
| Propeller boss cap fins | 5.95 | -0.4% | -0.4% |
| Asymmetric rudder | 5.98 | -0.2% | -0.2% |
| Propeller rudder bulb | 5.98 | -0.2% | -0.2% |
| Waste heat recovery | 6.00 | -0.4% | -0.4% |
| Air bubble lubrication | 5.78 | -1.5% | -1.4% |
| Air cavity lubrication | 5.83 | -1.0% | -0.9% |
| Hull coatings | 5.75 | -1.7% | -1.7% |
| Hull maintenance | 5.88 | -0.5% | -0.5% |
| Regular propeller polishing | 5.95 | -0.4% | -0.4% |
| Liquid Natural Gas for auxiliary power | 5.88 | -20.3% | -20.1% |
| Liquid Natural Gas for main engine | 5.98 | -4.5% | 1.1% |
| Liquid Natural Gas for both | 5.69 | -24.8% | -22.4% |
| Soft sails | 5.88 | -0.8% | -0.8% |
| Wind engine | 6.01 | 0.0% | 0.1% |
| Kite | 6.00 | -0.2% | -0.2% |
| Optimise flow over openings | 6.00 | 0.0% | 0.0% |
| Covering hull openings | 5.98 | -0.2% | -0.2% |
| Variable speed pumps and fans | 5.94 | 0.0% | 0.0% |
| LED lighting | 6.00 | 0.0% | 0.0% |
| Optimisation of dimensions | 5.92 | -1.2% | -0.4% |
| LNG Fuel Cell for auxiliary power | 5.77 | -1.0% | -0.8% |
| Main engine tuning | 5.62 | -3.1% | -2.9% |
| Photovoltaic solar cells | 5.94 | 0.0% | 0.0% |

Table A.3: Output results from the SIM for LCS for a 130 000 tonne deadweight 15 knot Suezmax oil tanker calculated using the operating assumptions detailed in Section 5.3.

## Appendix B

# About Energy Technologies Institute - Heavy Duty Vehicle Effiency Programme

## B.1 Introduction to ETI HDVE

The "Energy Technology Institute Heavy Duty Vehicle Efficiency - Marine" (ETI HDVE) project is led by Rolls-Royce and is a collaboration between:

- Rolls-Royce (RR Marine AS, RR plc., RR Marine AB)
- MTU
- Marintek
- UCL

The £2m marine technology project seeks to increase the efficiency of British shipping by more than 30% [ETI, 2013]. This could be by accelerating the development of technologies to reduce $CO_2$ emissions from shipping that are likely to be developed in future in order to bring them to the market sooner. The ETI HDVE project is focusing on developing a range of highly efficient concept vessels by combining modelling techniques from academia with commercial knowledge and technology development expertise from industry. The vessel types under study are typical of those used to transport goods to, from and around the UK coastline. If successful, this project could lead to a further £8m being invested into a large-scale demonstration of a best vessel concept and the technologies it uses [ETI, 2013].

The project consists of three phases, from the initial modelling and development stage to the development of a large-scale marine demonstrator:

- Phase 1 - Develop ship and shipping system models and generate system concepts for each vessel and conclusions as to which technologies should be invested in.
- Phase 2 - Generate integrated plan for phase 2 technology developments, featuring all of the likely technologies and the overall budget and timescales required to bring them to a suitable technology maturity.
- Phase 3 - Generate high level design / make plan for Marine Demonstrator. In phase3, including budget estimate. This should incorporate all of the technologies in phase 2 that are relevant to the marine sector.

Much of the development of modelling tools that is carried out by UCL (Energy Institute and the Marine Design Group, Mechancal Engineering) occurs in Phase 1 of the ETI HDVE project.

All of the findings from the study work and put together a set of recommendations for technology investment in phase 2 and 3. The choice of technologies will weigh up the different aspects, including but not limited to:

- Synergy with similar ETI HDVE - Land project.
- TRL level.
- Originality of technology (including other research outside of HDVE project).
- Impact on vessel performance.
- Impact on UK fleet GHG emissions.
- Business case for future customers.
- Route to market (synergy with Rolls-Royce technology strategy).

## B.2 The role of the Ship Impact Model in phase 1

The Ship Impact Model (SIM) was used as the basis for the vessel modelling. The SIM had to be devoped to incorporate the additional ship types that are being examined in the project (Ro-Ro, Ro-Pax and OSV). Additional detail was added to the Ship Impact Model (SIM) such as the ability to specify multiple engines and controllable pitch propellers. In LCS (see Appendix A) this level of detail was not required because the technologies that were described were much simpler, though the scope of the project was larger; in comparison the ETI HDVE project is more focused on specific ships. The main aims were:

- Development of interfaces to integrate marine engineering models (such as for wast heat recovery) with ship models.
- To carry out simulations of the impact on the ship and performance from a ship-centric perspective.
- To produce inputs into the maritime model for simulation of the impact of the technologies from the broader techno-social-economic perspective.
- To work together on validating the new toolset against existing vessels with existing technology.
- To provide a user manual and support.

The ETI HDVE project allowed for further more detailed development and validation of the Ship Impact Model (SIM). Phase 1 began in May 2012 and was 15 months long. The emphasis throughout the ETI HDVE project has been on flexibility and in 2013 the project is focusing on sail assisted propulsion, waste heat recovery and hybrid marine system arrangements.

### B.2.1 About the Energy Technologies Institute

The Energy Technologies Institute (ETI) is a public-private partnership between global industries (BP, Caterpillar, EDF, E.ON, Rolls-Royce and Shell) and the UK Government. The ETI is focused on accelerating the deployment of affordable, secure low-carbon energy systems for 2020 to 2050 by demonstrating technologies, developing knowledge, skills and supply-chains and informing the development of regulation, standards and policy [ETI, 2013].

# Appendix C

# Ship Survey

## C.1 Introduction to ship survey

The purpose of this appendix is to provide some additional background to the ships that were selected as Whole Ship Models (WSMs) in Table 4.1.

The first three sections look at the development rate of technology in shipping and what is likely to change physically change shipping in future, while the last section examines the individual ship types in more detail and explains why they were selected.

This appendix is also important in establishing what the typical baseline ship is.

## C.2 Marine Technogical Development

Figure C.1 shows the key developments of materials and main propulsion technology over the past 250 years. A few ships were chosen such as the Dorthe Maersk, which had the first turbocharged Diesel engine [Pomeroy, 2010], and the Emma Maersk has pushed the limits of more recent technology and is also a testament to increased understanding of ship strength.

It is important to examine the time between introduction and development of a new technology and the time it took to implement it. In 1893 Rudolf Diesel ran his first engine, then in 1910 the first Diesel powered ship was invented, by the 1930's burning of HFO became a standard fuel. The first steam boat patent was in 1736, though the first steam boat did not appear until 1818 [Pomeroy, 2010]. The second example is more extreme, but it is probably fair to say that a new technology may take a maximum of around 15 years to implement. Less mature and efficient technologies would need more time to become widely adopted.

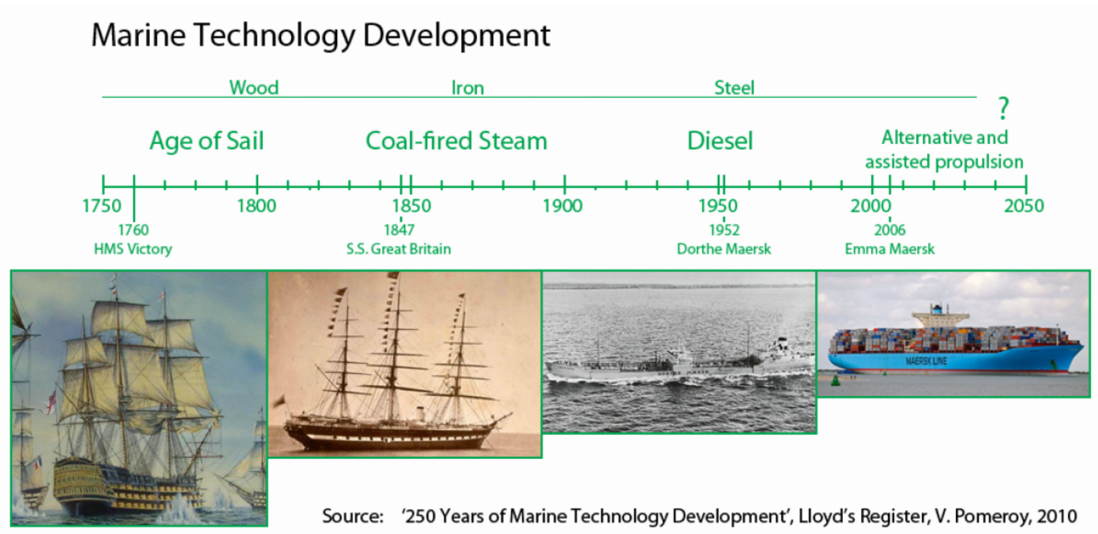


Figure C.1: Marine Technology Development Timeline

### C.2.1 Technology Readiness Level (TRL)

NASA originally developed Technology Readiness Levels (TRLs) as a way of meauring how close a component, system and/or product is to being ready for use or ready for a market [Mankins, 2009]. The TRLs developed by NASA give a detailed description of each level from initial inception, 1, to successful operation, 9.

Technological Readiness Levels as used by Rolls-Royce are almost identical to those used by NASA [Mankins, 2009]:

1. Basic principles observed and reported.
2. Technology concept and/or application formulated.
3. Analytical and experimental critical function and/or characteristic proof of concept.
4. Component and/or partial system validation in laboratory equipment.
5. Component and/or partial system validation in relevant environment.
6. System/subsystem model or prototype demonstration in relevant environment.
7. System prototype demonstration in an operational environment.
8. Actual system completed and service qualified through test and demonstration.
9. Actual system proven through successful mission operation.

The above TRL levels given below are written in a generic way that is applicable to the development of technologies that can be used to reduce $CO_2$ emissions.

## C.3 Future changes in the shipping industry

The possible opening of Arctic routes, such as the Northern Sea Route via the Barents Sea between Europe and the north Pacific Region, as a result of projected ice melting in the future is important. Increased air pollution in arctic regions is of particular concern because of the high vulnerability in these areas [Eyring et al., 2010]. Commercial ships in these regions will have to work in the arctic environment where the water is colder and may need additional regulations to help account for the sensitivity of arctic regions to pollution.

Sea level rise may leave some ports less useful and some low lying islands may become uninhabitable. However, overall these changes are unlikely to cause major changes in the global emissions from shipping [Eyring et al., 2010].

The changing infrastructure and capacities of ports and canals is also important. The most impotant of these is the Panama canal that is set to expand to its maximum capacity in the next decade. Table C.1 shows a comparison between the Panamax ship size and the new-Panamax ship size. Many current post-Panamax container ships will fit the new draught to beam ratio because container terminals also have a limited draught, the maximum depth of container terminals in the world is around 16 metres [Port of Felixstowe, 2011] [PSA Singapore Terminals, 2011]. Future new bigger ships could also create their own limitations, such as a Malaccamax ULCC (Ultra Large Container Carrier).

| Lock size | New Post-Panamax locks | Existing Panamax locks |
|---|---|---|
| Ship size (TEU) | 12 000 TEU | 4 500 TEU |
| Chamber beam | 55m | 33.5m |
| Vessel beam | 48.8m | 32m |
| Chamber length | 427m | 305m |
| Vessel length | 366m | 294.3m |
| Vessel draught | 15.3m | 12m |
| Vessel clearance | 3m | 0.6m |

Table C.1: Comparison of post-panamax and panamax lock sizes [Payer and Brostella, 2006].

This has large implications because Panamax size ships are one of the most common single ship sizes, by number of ships, and panamax ship are designed with constrained dimensions with a bias towards fitting cargo through the Panama canal rather than open-water performance.

It is also possible that in the future new ship types may be needed due to the demand for a new commodity (such as to support a hydrogen economy) or a new service (possibly due to changing transport links and affluence).

Wärtsilä looked at different scenarios for 2030 to see what ship types and hence propulsion would be needed in future [Wärtsilä, 2010]. It was assumed in all scenarios that fresh water would be scarce, shipping will continue to be an important part of the transport matrix and more environmentally friendly and economic ships would be required. Two possible new future ship types were perceived from this. A water carrier and a algae harvester (in order to use algae in the manufacture of biofuels).

## C.4 Survey of selected ship types

The focus of the work in Low Carbon Shipping - A Systems Approach (LCS) is on four international ship types, container ships, bulk carriers, oil tankers and LNG tankers. Container ships, bulk carriers and oil tankers (carrying product and crude) are all shown as having high specific $CO_2$ emissions in Figure fig:secondimoghgstudy2009. Roll-on/roll-off (RORO) ferries are not being considered because they are more for coastal trades and may vary more in configuration. Although figure fig:secondimoghgstudy2009 shows LNG carriers as having a lower specific $CO_2$ emissions, probably partly due to burning natural gas, they have been included in the study because of a potential increase in future trade and they are very different from other ship types.

Large commercial ships almost solely use 2-stroke low-speed Diesels with a direct drive (no gearbox) and single-screw [Clarksons, 2010]. Twin-screw ships may be used in certain politically sensitive regions, as the extra redundancy they appear to offer is not required because engines are very reliable, and in order to operate in shallower ports with a low draught. LNG carriers may have a different method of propulsion depending on the utilisation of the boil off gas (BOG).

In order to model existing ships with the time constraints of LCS, the characteristics of, at the most four, different size categories were examined for each of the four ship types and a representative ship was selected from each. The Length, Beam and Draft of the baseline parametric ship model was then selected based on the selected ships. Using these parameters the baseline parametric ship model can be used to calculate the amount of cargo carried and fuel used, which could then be validated against specific ships in the chosen size categories.

### C.4.1 Container Ship

In 1969 Encounter Bay became the first long range deep sea fully cellular container ship [Pomeroy, 2010]. Now all container ships are fully cellular.

#### C.4.1.1 Market survey

FigureC.2 shows the distribution of container ship sizes by the number of ships. 25% of container ships are of Panamax size with over 20% of panamax container ships have a length of around 290 to 294 metres (this is the maximum allowable length for transiting the panama canal, with the existing locks).

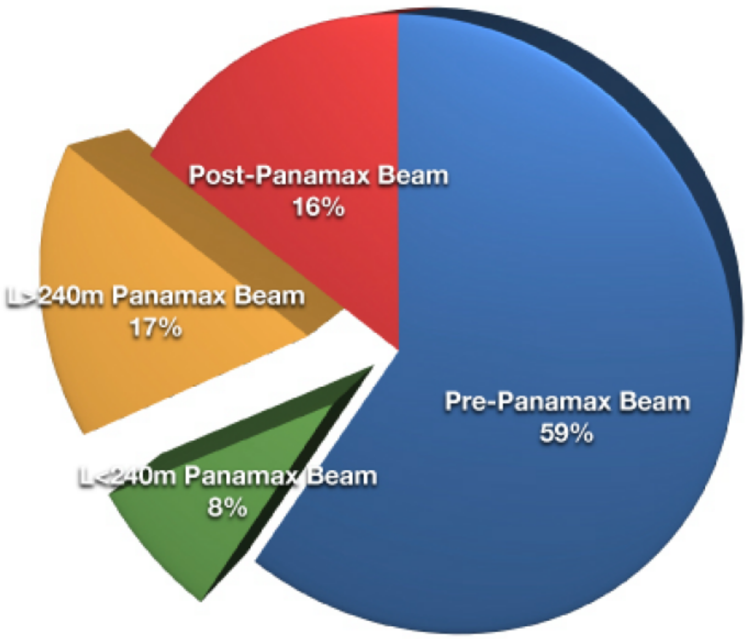


Figure C.2: Container Ship Market Survey [Clarksons, 2010].

The most common size feeders carry around 1000 TEU and 2000 TEU containers. A feeder ship of around 2000 TEU will be examined because ships smaller than this differ more in configuration and some are geared (have cranes) while some are not. While the design speed on most large container ships is around 25 knots the design speed of feeder ships is lower than this, at around 15 knots [Clarksons, 2010].

Table C.2 shows the selected ship sizes that were used for point designs. The ULCC (Ultra Large Container Carrier) has a twin superstructure arrangement but a single superstructure arrangement version has also be examined. The calculated beam over draft is also shown as this impacts stability, the Panamax beam over draft ratio is smaller than that of other ship sizes so that Panamax ships may be less stable.

| Container ships | Feeder | Panamax | Medium | Large |
|---|---|---|---|---|
| Design speed (knots) | 20 | 25 | 25 | 25 |
| Overall length (m) | 225 | 294 | 342 | 371 |
| Waterline length (m) | 219 | 280 | 325 | 350 |
| Beam (m) | 32.2 | 32.2 | 42.8 | 48.8 |
| Hull depth (m) | 19.8 | 21.0 | 24.6 | 29.9 |
| Design draught (m) | 12.3 | 12.5 | 13.0 | 14.5 |
| Cargo holds | 9 | 18 | 21 | 23 |

Table C.2: Selected container ship sizes.

The quoted ship container capacities are misleading because they represent the total slot capacity or the total number of spaces in which a standard height container may be stowed, the actual ship container capacity depends on the distribution of container weights [Lamb, 2004].

#### C.4.1.2 Typical arrangement and design considerations

For container ships, generally a combined engine room and accommodation superstructure two thirds aft is preferred. This offers few drawbacks in terms of space utilisation compared to a fully aft engine room arrangement and improves trim behaviour [Lamb, 2004]. This can be seen in figure C.3. The exceptions to this arrangement are twin superstructure arrangements adopted on ULCCs and a fully aft arrangement is normally adopted on smaller feeder ships.

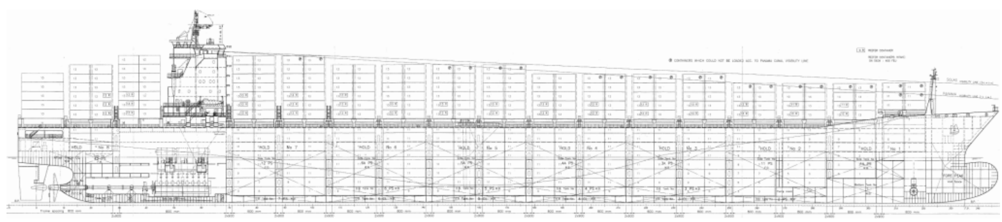

Figure C.3: Panamax 4444 TEU Panamax container ship chartered by Rickmers [Rickmers Shipowning & Shipmanagement, 2010].

Generally, container ships are faster than other commercial ship types and more dependent on wavemaking-resistance, hence they have slender hulls [Lamb, 2004].

An average electrical load value for a refrigerated 40 foot container should be taken as 4kW to get electrical demands that correlate with the supplied auxiliary loads of existing ships [RINA, 2007]. However, a reefer container in full chill mode typically uses between 10kW and

13kW of power and has a mass of over 20 tonnes [Lamb, 2004]. So they should be stored below deck for stability purposes, requiring ventilation in the holds to remove heat. From looking at manufacturers data it is also evident that containers storing frozen produce uses about 6kW less power than containers storing refrigerated produce [Daikin Industries Ltd., 2010], this is likely due to having to recirculate air more for chilled produce compared to frozen produce.

Fuel is normally stored in wing tanks so the effect on stability when fuel is used up is minimal and ballast can be placed in double bottom tanks where it is more effective [Lamb, 2004]. Adequate subdivision for 40 foot container holds can frequently be achieved by make every other transverse bulkhead a watertight bulkhead [Lamb, 2004].

ULCCs have a high installed propulsion power compared to other ship sizes and types and push the technical boundaries of ship design. Understanding the structural behaviour of very thick plate with regard to toughness and crack arrestability is also very important [Shi et al., 2006]. For example, when the Emma Maersk was constructed Mecklenburger Meallguss delivered world's largest propeller at the time, 9.6m in diameter, 131 tonnes, which also has specially developed blade tips to help mitigate cavitation. Reportedly there is a 150 tonne, 10.4m diameter propeller available [Shi et al., 2006]. The Emma Maersk is unusual in that it has a single superstructure arrangement. Although a single superstructure arrangement is still viable, all the design concepts by Hyundai Heavy Industries/GL and Bureau Veritas and Lloyds register (12500-13000 TEU designs) favour the two island concept (deckhouse forward and engine casing aft) [Shi et al., 2006]. Recent planned and new builds, such as the Maersk Triple-E class also favour a twin superstructure arrangement [IMarEST, 2011c]. The technical advantages for two island concept are compliance with SOLAS visibility requirements [IMO, 2004], reduced concerns with engine/shaft system (due to a shorter shaft), reduced vibration in accommodation areas and compliance with strength/deflection requirements.

The next limit for a ULCC is the Malaccamax container ship, which has a beam is 60m, this is approximately 18000TEU [IMO, 2004] (and 48.8m for a new-Panamax container ship [Payer and Brostella, 2006]). Several large terminals are already equipped with 64 metre outreach cranes [Shi et al., 2006] to load/unload container ships of this size. As the Malaccamax design draft is 21 metres, the maximum draft of container ships is limited by terminal constraints, drafts of large ports are not more than 16 metres [Shi et al., 2006] and the new-panamax draft is 15.3 metres [Payer and Brostella, 2006].

Summary of ULCC Limitations:

- Engine size (power, mass and width), this can be reduced for twin screw ships.
- Single screw Propeller size (single casting size), this can be reduced for twin screw ships.
- Hull Girder Strength (main strength deck steel thickness).
- Infrastructure Constraints (size and capacity of ports, canals and shipyards).
- Structural Limitations (such as a lack of understanding of inherent flexibility and behaviour of very thick plating)
- Container stacking limits (stacks can be a maximum height of 9 to 10 containers [RINA, 2010b])
- Market constraints (less flexible)
- Big ship problems (manoeuvring, fire salvage)

#### C.4.1.3 Future trends

Container ships transport commodities of high value (including perishable goods). The future market trends are dependent on freight rate and fuel prices. More recent container ships are designed for lower speeds because of high fuel prices and low freight rates, the Maersk Triple-E is a prime example of this as it is designed for 23 knots instead of 25 knots [IMarEST, 2011c]. A lower top speed allows operation in a more fuel efficient operating envelope and especially in the case of the Maersk Triple-E class, allows a fuller more U-shaped hull form that can carry more containers.

The trend for slower bigger ships means that the power and propeller loading requirements for larger ships, which were surpassed by the Maersk E Class, are no longer limits to the building of ULCCs. Twin-screw ULCCs reduces propeller loading and may increase efficiency as well as make draught constraints easier to meet.

### C.4.2 Bulk Carrier

Bulk carriers are designed for the carriage of dry cargo in bulk. The major dry bulks are iron ore, coal, grain and bauxite [Lamb, 2004]. These cargoes are of low value (especially when compared to a container ship) and are non-perishable, so design speeds of around 15 knots are economically viable. They normally have a single deck and topside tanks and hopper tanks in the top and bottom corners, respectively, of the hull, around the cargo hold [Lamb, 2004]. These tanks are normally used for ballast, especially on empty return trips.

### C.4.2.1 Market survey

Table C.3 and figure C.4 show the number of ships in each size category. The more detailed breakdown in table C.3 shows that although there are approximately four times the number of handysize and handymax ships compared to capesize ships the total deadweight is about the same.

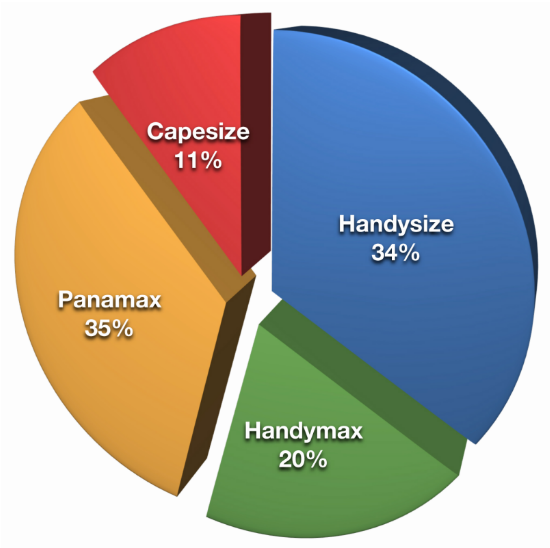


Figure C.4: Bulk carrier market survey [Clarksons, 2010].

### C.4.2.2 Typical arrangement and design considerations

The superstructure is normally located aft. As with all other types of ship, smaller feeder ships may carry a mixture of cargoes, which could include dry bulk, wet bulk and/or containers. See figure C.5.

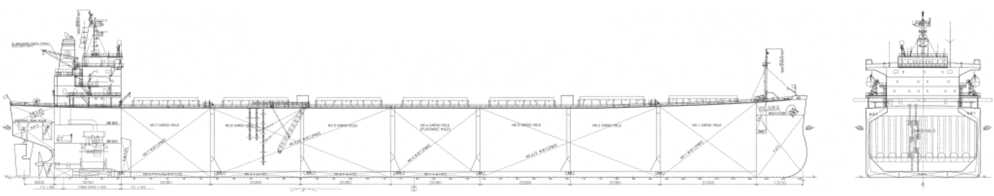

Figure C.5: Panamax Bulk Carrier Clara Chartered by Johann M. K. Blumenthal

Bulk carriers have a large block coefficient and a long parallel midbody and rectangular midship section [Lamb, 2004], as they are normally designed for speeds around 15 knots where frictional resistance is the most dominant.

The density of cargos can vary greatly from heavy ore (weight limited design) to grain (volume limited design) [Lamb, 2004]. Normally the ballast condition generates the highest still water

| Ship size | Lowest deadweight | Highest deadweight | Number | Total deadweight |
|---|---|---|---|---|
| Handysize | 10.2 kte | 35.0 kte | 788 | 20336.1 kte |
| Handymax | 35.0 kte | 50.4 kte | 456 | 19054.7 kte |
| Panamax | 50.4 kte | 82.7 kte | 807 | 52998.8 kte |
| Capesize | 82.8 kte | 259.6 kte | 246 | 38530.6 kte |

Table C.3: Bulk carrier size categories of market survey. The basic size category limits came from ship design and construction [Lamb, 2004] and they were combined with the market survey [Clarksons, 2010].

| Bulk carriers | Handysize | Handymax | Panamax | Capesize |
|---|---|---|---|---|
| Design speed (knots) | 15 | 15 | 15 | 15 |
| Overall length (m) | 172 | 197 | 225 | 300 |
| Waterline length (m) | 168 | 193 | 219 | 295 |
| Beam (m) | 27.0 | 28.0 | 32.2 | 50.0 |
| Hull depth (m) | 14.3 | 15.0 | 19.8 | 25.0 |
| Design draught (m) | 9.8 | 10.8 | 12.3 | 18 |
| Cargo holds | 5 | 6 | 7 | 9 |

Table C.4: Selected bulk carrier sizes.

bending moments [Lamb, 2004], rather than the heavy ore condition.

#### C.4.2.3 Future trends

High tensile steel has been used extensively for hull structures in order to minimise lightship weight [Lamb, 2004].

For single hull bulk carriers the side shell is the weakest point and can be damaged by corrosion and cargo handling [Lamb, 2004]. More and more new builds are double hulled [Clarksons, 2010] amid safety concerns. Although double hulled ships also provide a smooth inner surface, building costs may be higher and there may be a reduction in deadweight [Lamb, 2004].

### C.4.3 Oil Tanker

For oil tankers, similar to bulk carriers, economics dictate slow speeds and full hull forms, typically between 14 and 16 knots [Lamb, 2004].

#### C.4.3.1 Market survey

The future emission production potential of oil tankers is of more interest compared to other tanker types because their demand is dependent upon the availability of oil and because crude oil carriers in particular represent some of the largest ships in the tanker fleet. Table C.5 shows a complete breakdown of the tanker market from the oil tanker market survey that was carried out. As one would expect, smaller ships mainly consist of product tankers and chemical tankers, which are more specialist ships. As with bulk carriers although a lot of the ships in the market are smaller a much larger proportion of deadweight is carried by larger ships.

The main difference between oil tankers and other ship types is that they are generally larger ships, so the selected point designs should reflect this.

Aframax size tankers are based upon the Average Freight Rate Assessment (AFRA) tanker rate system. This means aframax size ships could also be suezmax size ships. This is interesting as it is possible that new low $CO_2$ regulations could create similar low $CO_2$ tax sizes. As with the other market surveys, panamax ships are those with 32m, panamax, beam. The divides that were used to categorise the ship sizes are shown in table C.5.

| Ship size | Lowest deadweight | Highest deadweight | Total | Tanker | Other Oil | Product/ Chemical |
|---|---|---|---|---|---|---|
| Medium Range | 48 te | 44370 te | 7693 | 565 | 2161 | 4967 |
| Short Panamax | 44481 te | 53755 te | 995 | 13 | 57 | 925 |
| Panamax | 55019 te | 84440 te | 402 | 112 | 0 | 290 |
| Aframax | 84992 te | 120232 te | 893 | 676 | 0 | 217 |
| Suezmax | 121109 te | 193050 te | 416 | 408 | 0 | 8 |
| VLCC | 214862 te | 321300 te | 546 | 546 | 0 | 0 |
| ULCC | 441561 te | 441585 te | 2 | 2 | 0 | 0 |

Table C.5: Market survey of tanker fleet [Clarksons, 2011]. The medium range category is for smaller medium range and coastal ships and the short panamax category represents ships that 32m, panamax, beam and have a length of less then 200m.

Figure C.6 shows how the number and hence significance of each ship size changes when considering the oil tankers only and the whole tanker market (including product and chemical carriers).

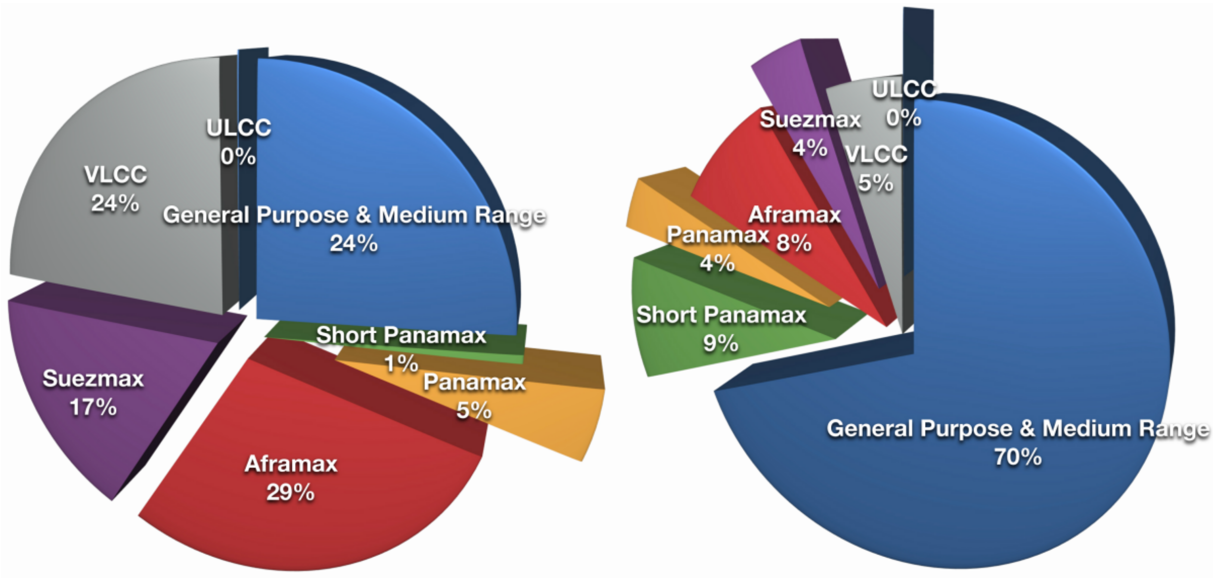


Figure C.6: Oil tanker, including shuttle tankers, market Survey (left) and overall tanker market survey (right) [Clarksons, 2011].

| Oil tankers | Panamax | Aframax | Suezmax | VLCC |
|---|---|---|---|---|
| Design speed (knots) | 15 | 15 | 15 | 15 |
| Overall length (m) | 222 | 244 | 275 | 333 |
| Waterline length (m) | 217 | 240 | 270 | 328 |
| Beam (m) | 32.2 | 42.0 | 48.0 | 60.0 |
| Hull depth (m) | 18.5 | 21.2 | 23.2 | 30.5 |
| Design draught (m) | 12.3 | 14.9 | 17.0 | 21.5 |
| Cargo holds | 6 | 6 | 6 | 15 |

Table C.6: Selected oil tanker sizes

### C.4.3.2 Typical arrangement and design considerations

As with Bulk carriers the superstructure is normally located aft. Oil tankers also have a pump room and slop tanks located forward of the superstructure for pumping oil and cleaning tanks, respectively (see Figure C.7). Free-surface effects mean that two or three (on bigger ships) longitudinal subdivisions are necessary [Lamb, 2004].

For product and chemical carriers where cross contamination is an important consideration the pump room is sometimes eliminated in favour of submerged pumps in each tank [Lamb, 2004]. Chemical and product tankers also differ in that a double hull may not be necessary [Lamb, 2004].

Residual strength after damage and damaged stability, as buoyancy is provided by outer tanks, are important considerations [Lamb, 2004].

The carriage of oil imposes additional requirements in order to minimise oil outflow in the event of damage and additional fire fighting requirements. The most significant of these being the MARPOL double hull requirements. Large volumes of inert gas are also to be provided to holds when discharging and on passage [Lamb, 2004].

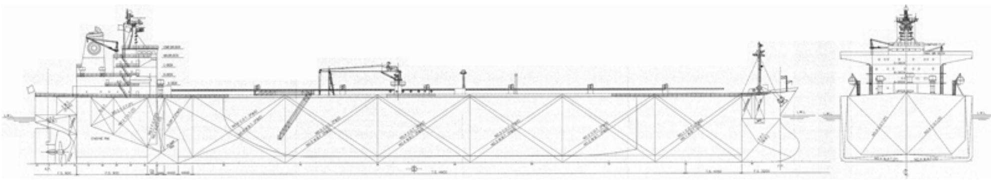

Figure C.7: Aframax Oil Tanker Angelica Schulte chartered by Bernard Schulte

The much lower speed of oil tankers compared to container ships means that generally ULCCs are driving engine and propeller size. For oil tankers fatigue and corrosion are more of a concern [Lamb, 2004].

#### C.4.3.3 Future trends

What is likely to change the oil tanker market considerably, in the long-term, is the role oil and alternative fuels will take as a energy source in the future. In the short-term new regions, such as in the arctic, could be exploited.

### C.4.4 LNG Carriers

The focus of the gas carrier ships is on LNG (Liquid Natural Gas) carriers because should natural gas be adopted more widely as a future fuel as an alternative to oil-based fuels then the demand for LNG carriers will increase. More generally, the most significant cargoes carried by gas carriers are LNG, LPG and Ammonia [Lamb, 2004].

Methane has a critical temperature of -82°C (it cannot be liquefied by application of pressure above this temperature). LNG carriers are designed to carry gas in liquid form at atmospheric pressure and a temperature in the region of -164°C. This requires the ship design to protect the steel structure from low temperature in order to assist in reducing the loss of gas and avoiding leakage [Taylor and Tang, 2006].

For liquified natural gas carriers tank types can be divided into three main categories, self-supporting, membrane and semi-membrane [Taylor and Tang, 2006]. Self-supporting tanks are pressure vessels such as Moss Rosenburg spherical tanks, Gas Transport and Technigaz are associated with membrane tanks [Lamb, 2004]. Unlike membrane tanks semi-membrane tanks do not extend above the depth of the hull.

#### C.4.4.1 Market Survey

Unlike other ship types there are not any established size categories for LNG carriers this is partly because the ships are not driven by canal limitations because they are considerably smaller than the other ship types. So the LNG carriers were categorised according to table C.7 and the number of ships in each size category is shown in figure C.8.

The only size vessels that reach a well recognised (by the industry) beam and length limit are Q-max vessels. A Q-max size vessel is the maximum size ship that can be accommodated at the Ras Laffan gas terminal, Qatar. A Q-max LNG carrier has a length of 345, a beam of 55 and a draft of 12 metres [Qatargas, 2006]. A Q-flex size vessel is just below Q-max size vessels.

| Ship size | Lowest deadweight | Highest deadweight | Total | Total deadweight |
|---|---|---|---|---|
| General purpose | 817 te | 27235 te | 20 | 234130 te |
| Medium | 35760 te | 69991 te | 38 | 2165963 te |
| Medium-large | 70328 te | 79983 te | 161 | 12105616 te |
| Large | 80229 te | 97730 te | 99 | 8394197 te |
| Q-flex | 100216 te | 122079 te | 31 | 3475497 te |
| Q-max | 129851 te | 152600 te | 11 | 1499465 te |
| Post Q-max | 154940 te | 154940 te | 3 | 464820 te |

Table C.7: Market survey of LNG tanker fleet [Clarksons, 2011].

The majority of LNG carriers are were categorised as Medium-Large (see table C.7), which have a deadweight between 70000 and 80000 tonnes. The high number of vessels around Medium-Large and Large size (between 7000 and 10000 tonnes deadweight) also means that in terms of overall deadweight and carbon emissions this size of ship is the most significant. This can be seen in figure C.8.

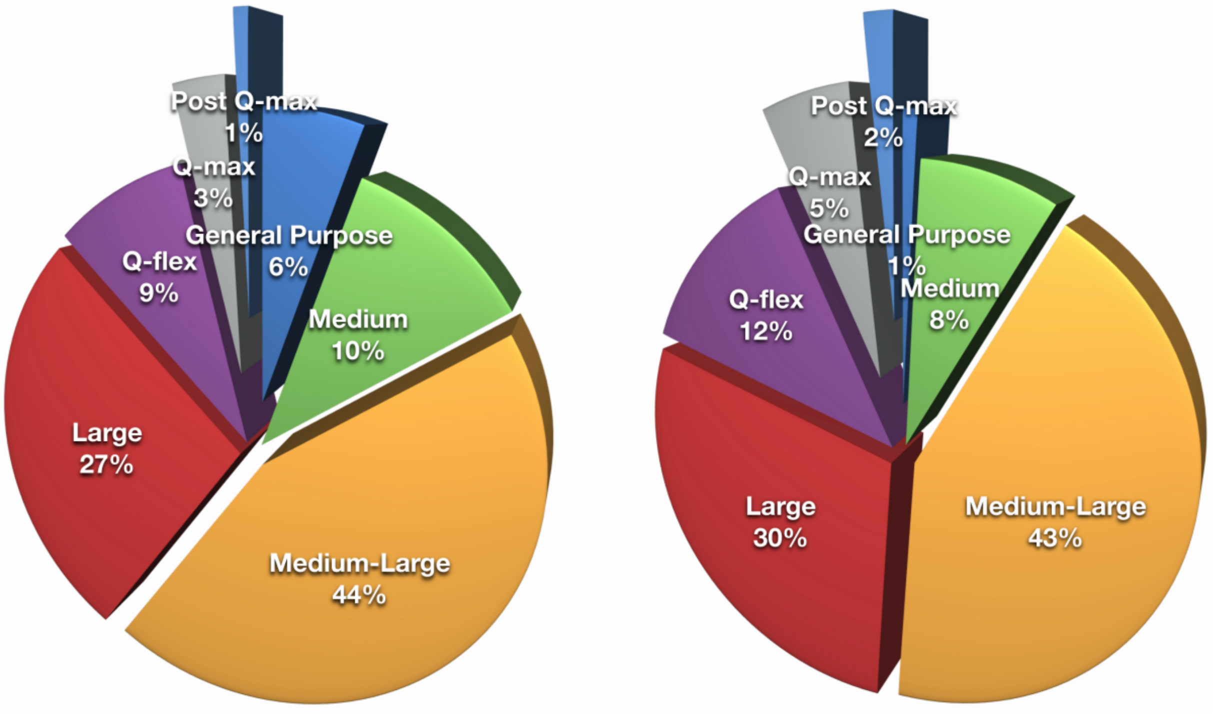


Figure C.8: LNG Tanker Market Survey by number of ships (left) and LNG Tanker Market Survey by deadweight (right) [Clarksons, 2011].

| LNG tankers | Medium-large | Q-flex |
|---|---|---|
| Design speed (knots) | 20 | 20 |
| Overall length (m) | 287 | 315 |
| Waterline length (m) | 274 | 301 |
| Beam (m) | 43.4 | 50.0 |
| Hull depth (m) | 26.0 | 27.0 |
| Design draught (m) | 11.8 | 12.3 |
| Cargo holds | 4 | 5 |

Table C.8: Selected LNG tanker sizes

It is also apparent that the majority of LNG carriers are limited to 12 metres draught due to the draught limitations of LNG loading and re-gasification terminals [Clarksons, 2011] and have a design speed of around 18 to 20 knots (not including smaller general purpose size ships) [Clarksons, 2011].

In current order books the membrane system has become increasingly more popular [Noble, 2007]. Part of this increase in the use of membrane tanks is due to the higher cost of bringing Moss (spherical containment) ships through the Suez Canal and in part is due to the fact that the three largest Korean shipyards have adopted membrane systems as their primary solution for LNG ships [Noble, 2007]. The membrane LNG carrier is capable of loading more than 8% more LNG cargo in identical principal ship dimensions as a spherical LNG carrier [Moon et al., 2005].

#### C.4.4.2 Typical arrangement and design considerations

The overall layout is similar to that of the conventional oil tanker, from which it evolved [Lamb, 2004]. The majority of LNG carriers are steam-powered, using boil-off gas (BOG) for part of their fuel requirements [Noble, 2007] (a compressor plant installed instead of re-liquefaction plant) [Lamb, 2004]. Rather than having a pump room, like a oil tanker, LNG carriers use submerged pumps in the holds. The LNG tanker shown in figure C.9 has two cargo pumps and one stripping pump [Exmar, 2010].

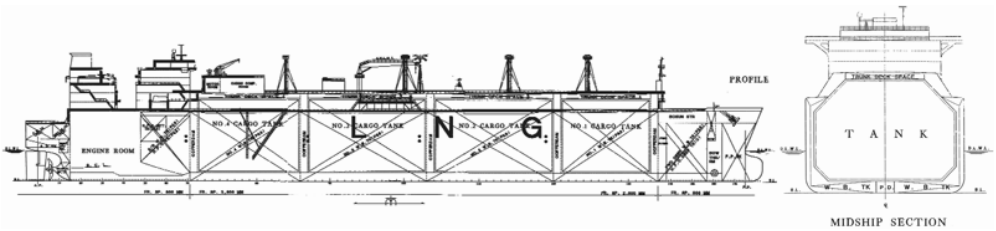


Figure C.9: Medium-Large (see table C.7) LNG Tanker Excalibur chartered by Exmar [Exmar, 2010].

Adequate insulation is required to reduce cargo loss, especially with membrane tanks. 0.1% of Cargo evaporates everyday [Chang et al., 2008]. A re-liquefaction plant can be used to recover the evaporated gas, however a re-liquefaction plant is typically installed on LNG carriers with more than 200000 $m^3$ capacity and could require up to 6 MW of electric power [Hansen and Lysebo, 2006]. It is normal practice to use the boil off gas (BOG) as a fuel [Chang et al., 2008]. This means when slow steaming and increasing the time of the voyage for LNG Carriers may be less attractive, especially if the BOG is not used as a fuel.

There have been concerns over the robustness of membrane tanks to sustain sloshing loads [Noble, 2007]. Divides in the tanks are also avoided in order to minimise the ships surface area coming into contact with the LNG, minimising heat transfer. From observations of existing ships the double hull thickness is driven by the required insulation rather than the structure required to resist longitudinal bending (it is more than adequate for this) [RINA, 2010a].

Approximately 50% of the LNG carrier market use BOG to fire boilers, producing steam and driving steam turbines. 25% of the market uses low-speed Diesel engine propulsion with re-liquefaction and the remaining 25% use Medium-speed dual-fuel Diesel-electric propulsion [Chang et al., 2008].

For large LNG carriers (greater than 210,000 cubic metres), twin screw designs are preferred, in contrast with other large ships, such as container ships and large tankers, which are single screw. Shallow draft restrictions of around 12.0 m, imposed by many LNG loading and re-gasification terminals limit the size of the propeller, and therefore, limit the propulsion efficiency that can be gained from a single screw hull form. High beamed, shallow draft ships can benefit significantly in propulsive efficiency by using twin screw arrangements [Noble, 2007].

The hull form of LNG carriers is more slender compared to bulk carriers because of a higher speed. The more slender forward section and draft limitation means that the cargo holds take up a smaller proportion of the length of the ship compared to a a equivalent sized bulk carrier or oil tanker, this may also be because the forward and aft most tanks have more surface area in contact with the LNG and so are less efficient.

#### C.4.4.3 Future trends

Since the introduction of the first Diesel powered LNG carriers the ratio of Diesel powered ships to steam-powered ships has increased. With about half of the Diesel powered LNG carriers having dual-fuel medium-speed Diesel-electric plants and half having direct-drive slow-speed Diesel plants with BOG re-liquefaction. [Noble, 2007].

Compared to other ship types the fleet is fairly small in overall size and in ship size. High design speeds of around 18 to 20 knots (not including general purpose size ships) [Clarksons, 2011] compared to 15 knots for oil tankers [Clarksons, 2010] may be an indicator that fleet is operating to capacity (this design speed is necessary to meet demand) and further ships would lower the design speed and make the fleet more efficient. A increase in demand for natural gas may also cause a increase in the capacity of the fleet and in the demand for bigger ships.

### C.4.5 Logistics and port and canal infrastructure

With all ship designs logistics and the efficiency of unloading and loading of ships are a key drivers that introduce requirements into the ship design.

For instance, in order to carry heavy cargoes such as iron ore bulk carriers load alternate holds to reduce loading/unloading times rather then half filling the holds which would be better from a ship design perspective. This means the driving loading case for the bulkhead and double bottom structure is having holds full of heavy cargoes next to empty holds. A trade-off may exist between the length of the route and hence the proportion of the time spent loading/unloading and the ship design. Open-top container ships could increase productivity on shorter routes, their application is limited due to container stacking height limits and additional structure further from the neutral axis required to meet freeboard requirements. This or any other ship with a unique design concept is based on the fundamental tenet of the 'equivalent level of safety' [Alman and Fisher, 1995]. Gearing and hatch sizes are also important and depend on the facilities of the ports as well as logistics.

In some ways ship size drives port infrastructure, however when considering future ships there will be financial or physical limits to the depth ports can be dredged to.

LNG Carriers generally seem less constrained by port or canal constraints because they are smaller in size as there are fewer smaller ships compared to other markets. Although, the biggest Q-max size LNG carriers are constrained by port infrastructure. As with oil tankers, in certain areas there is also a trade-off between using pipelines and shipping for distribution.

### C.4.6 Summary of emission reduction potential from selected ships

Regional carbon emission regulation or carbon taxes are likely to drive the size and configuration of ships in future.

The container is an efficient way of transporting goods door to door but it does not mean that, but does not pack cargo together very efficiently. Container cargoes are not very dense, hence having to store containers on deck. The average weight of a container in the hold was found to be 13 tonnes dividing this by the volume of a container gives a density of 0.34 tonnes/m$^3$, LNG is the closest cargo density to this with a density of 0.47 tonne/m$^3$.

The potential of reducing the auxiliary power requirement for container ships is not to be underestimated, oil tankers can also have high cargo heating loads. Container ships have the most potential for emission reduction because of their high design speeds, while LNG carriers have the least potential due to their utilisation of natural gas and due to being the smallest in size and in number of ships compared to the other three ship types.

## Appendix D

# Publications

## D.1 Conference Papers

These papers have been referenced where they have been referred to and can also be found in the References section:

*Calleya, J., Mouzakis, P., Pawling, R., Bucknall, R. and Greig, A. (2011). "Assessing the Carbon Dioxide Emission Potential of a Natural Gas Container Carrier". International Conference on Technologies, Operations, Logistics and Modelling for Low Carbon Shipping, LCS 2011, Glasgow, UK, pages 309-320.*

*Calleya, J., Pawling, R., Greig, A. and Bucknall, R. (2011). "Assessing the dependence of carbon dioxide emission reduction potential of natural gas on the size and topology of container carriers and other ship types". Gas Fuelled Ships Conference 2011, pages 75-85.*

*Calleya, J., Pawling, R., Smith, T. and Greig, A. (2012). "Ship Design and Evaluation for a Greenhouse Gas constrained future [rewritten for the Naval Architect in January 2013 under the title 'Calibrating the Future' ]". The Environmentally Friendly Ship, The Royal Institute of Naval Architects.*

## D.2 Journal Paper

In preparation to be published in 2014:

*Calleya, J., Pawling and A., Greig. (2014). "Ship Impact Model for Technical Assessment and Selection of Carbon Dioxide Reducing Technologies (CRTs)".*

# Glossary

**AIS** The Automatic Identification System (AIS) is a ship tracking system for identifying and locating vessels. AIS integrates a standardised VHF transceiver with a positioning system such as a GPS receiver allowing vessels to be tracked by AIS base stations, located along coast lines, or by Satellites. The International Maritime Organization's (IMO) international convention for the Safety of Life at Sea (SOLAS) requires AIS to be fitted aboard international voyaging ships with a gross tonnage over 300 tonnes, and all passenger ships regardless of size. AIS can be used to track shipping activity with the aim of reducing $CO_2$ emissions, however care must be taken when interpreting the data as not all the fields provided by AIS have to be completed by the ship operstor and any sensors reported by AIS, such as in order to measure speed, have to be correctly calibrated.

**auxiliary power** Auxiliary power is power used for hotel, cargo requirements and supporting systems. Everything except the power used for propulsion and cargo heating boilers are covered under auxiliary power. This is a fluctuating but fairly consistent power requirement, especially when compared to propulsion power, which has a large variation with speed. For most cargo ships auxiliary power is provided by a set of generating sets that is separate from the propulsion engines. See Main Engine.

**baseline ship** The baseline ship is the input ship specification that is used for analysis before any consideration of Carbon Dioxide Reducing Technologies (CRTs). This baseline represents a typical current ocean going cargo ship. A modified baseline ship with different CRT combinations can be compared to the baseline ship with no CRTs to find out the percentage performance change due to a CRT. See Carbon Dioxide Reducing Technology (CRT).

**BOG** Boil Off Gas (BOG) is Liquefied Natural Gas (LNG) vapour that boils off as heat leakage warms the LNG. Industry practice is to store the LNG at its boilig point (-163 degrees celcius) for the pressure at which it is stored. As the BOG boils off, the heat the BOG required for the phase change cools the remaining liquid. Some LNG carriers use the BOG for fuel while others use a re-liquefaction system. See Liquified Natural Gas (LNG).

**CCC** The Committee on Climate Change (CCC) is an independent UK body established under the Climate Change Act (2008). The CCC advises the UK Government on setting and meeting carbon budgets and on preparing for the impacts of climate change [`http://www.theccc.org.uk/`].

**$CO_2$** Carbon Dioxide ($CO_2$) is a greenhouse gas (GHG). Although the longevity of Carbon Dioxide in the atmosphere may not be well understood, it is widely accepted that Carbon Dioxide is the worst of the Greenhouse Gases due to its persistence and irreversibility in the atmosphere over time [Nature, `http://www.nature.com/climate/2008/0812/full/climate.2008.122.html`].

**cold ironing** Cold Ironing is the practice of using electricity provided by the port. Cold Ironing can potentially reduce $CO_2$ emissions from ships, but the overall $CO_2$ emission reduction also depends on the ship fuel and the source of the energy used in port. See Carbon Dioxide Reducing Measure (CRM).

**CRM** A Carbon Dioxide Reducing Measure (CRM) is any measure that reduces the Carbon Dioxide (CO2) emissions of a ship or a fleet of ships. A CRM can be categorised as an operational measure or a Carbon Dioxide Reducing Technology (CRT). The most important CRM is changing operational speed. See Low Carbon Shipping (LCS), Carbon Dioxide Reducing Technology (CRT) and operational speed.

**CRT** A Carbon Dioxide Reducing Technology (CRT) is any technology that can be incorporated into a ship (this could be either a retrofit or new build) that reduces the Carbon Dioxide (CO2) Emissions of the ship compared to the original ship design (before modification). A CRT is a type of Carbon Dioxide Reducing Measure (CRM) and can be categorised as reducing propulsion power, reducing auxiliary power or using fuel more efficiently (increasing energy/$CO_2$ emissions, including using alternative fuels to oil). See Carbon Dioxide Reducing Measure (CRM), Low Carbon Shipping (LCS), Retrofit and New Build.

**design speed** Design speed is the speed that a ship is designed to transit at, it is normally the highest single speed that can be continuously maintained at an efficient Specific Oil Fuel Consumption (SOFC). There are added benefits, such as in Main Engine weight and SOFC by designing a ship to operate at the correct design speed. Sometimes used interchangeably with operational speed but not to be confused with operational speed. See design condition, Maximum Continuous Rating (MCR), Specific Oil Fuel Consumption (SOFC), Main Engine, speed and operational speed.

**ECA** MARPOL Annex VI Regulations for the Prevention of Air Pollution from Ships establishes certain Emission Control Areas (ECAs) with more stringent controls on sulphur oxide ($SO_x$) and nitrogen oxide ($NO_x$) emissions [`http://www.imo.org/OurWork/Environment/PollutionPrevention`].

**EEDI** The Energy Efficiency Design Index (EEDI) is for new ships and was created in order to stimulate innovation and technical development of all elements influencing the energy efficiency of a ship from its design phase. At the 62nd MEPC meeting at the IMO in July 2011 it was agreed that the Energy Efficiency Design Index (EEDI) will become mandatory for new ships as well as the Ship Energy Efficiency Management Plan (SEEMP) for all ships over 400 gross tonnage. The EEDI entered into force on 1 January 2013 and added to Regulations for the Prevention of Air Pollution from Ships (MARPOL Annex VI). See Regulations for the Prevention of Air Pollution from Ships (MARPOL Annex VI) and Marine Environment Protection Committee (MEPC) [Marine Environment Protection Committee - Circ.681].

**EEOI** Energy Efficiency Operational Indicator (EEOI) is an indicator for the energy efficiency of a ship in operation, as an expression of efficiency expressed in the form of Carbon Dioxide ($CO_2$) emitted per unit of transport work. See Regulations for the Prevention of Air Pollution from Ships (MARPOL Annex VI) and Marine Environment Protection Committee (MEPC) [Marine Environment Protection Committee - Circ.684].

**embedded carbon** Carbon Dioxide ($CO_2$) is emitted at all stages of a manufacturing process, from the mining of raw materials to the distribution process is termed embedded carbon. The embedded carbon of shipping is associated mainly with the manufacture, ship-breaking and recycling of the ship. The emissions generated during use are not part of the embedded carbon and are the operational $CO_2$ Emissions. Embedded carbon is difficult to quantify and additional uncertainties may arise when considering what embedded carbon is attributable to the shipping industry and what is attributable to manufacturing industries. See Carbon Dioxide ($CO_2$).

**ETS** A limit is set on the amount of pollutant that may be emitted, this is then allocated or sold to firms in the form of emission permits (or carbon credits), which represent the right to emit a specific volume of pollutant. Firms that need to increase their volume of emissions must by buy permits from those who require fewer permits. The buyer is paying a charge for polluting, while the seller is being rewarded for having reduced emissions. In theory those who can reduce emissions at the lowest cost will do so, achieving the pollution reduction at the lowest cost to society. A ETS is a type of Market Based Measure (MBM).

**fuel infrastructure** The fuel infrastructure is used to describe any of the processes and facilities required to manufacture and distribute a fuel. This is similar to the fuel chain or lifecycle of the fuel.

**GHG** A Greenhouse Gas (GHG) is a gas that contributes to the greenhouse effect by absorbing infrared radiation. Carbon dioxide and chlorofluorocarbons are examples of greenhouse gases. The greenhouse effect is the trapping of the sun's warmth in a planet's lower atmosphere, due to the greater transparency of the atmosphere to visible radiation from the sun than to infrared radiation emitted from the planet's surface [ODO, `http://oxforddictionaries.com/`].

**HFO** Heavy Fuel Oil (HFO) is a residual fuel that consists primarily of the residue of the crude oil refining process after virtually all of the higher quality hydrocarbons have been removed from the crude oil. It is a highly polluting low-grade fuel. This means that it is inexpensive and consists of a number of long chain hydrocarbon molecules and has a high sulphur content as well as containing a number of other impurities. HFO is normally used in large low-speed two-stroke marine Diesel engines. See Main Engine.

**IMO** The International Maritime Organisation (IMO) is the United Nations specialised agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships [`http://www.imo.org/About`].

**Kyoto Protocol** The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC). The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the European community for reducing Greenhouse Gas (GHG) emissions. These amount to an average of five per cent against 1990 levels over the five-year period 2008-2012. The major distinction between the Protocol and the Convention is that while the Convention encouraged industrialised countries to stabilise GHG emissions, the Protocol commits them to do so. See United Nations Framework Convention on Climate Change (UNFCCC) and Greenhouse Gas (GHG) [http://unfccc.int].

**LCS** Low Carbon Shipping - A Systems Approach (LCS) is a UK centric research project majority funded by the RCUK energy programme between 5 UK universities and supported by industry. The purpose of LCS is to examine the potential of different Carbon Dioxide Reducing Measures (CRMs) available between the present day and 2050 in order to investigate what proportion of the Carbon Dioxide ($CO_2$) emissions from international shipping are attributable to the UK and how best to implement regional regulatory measures. See Carbon Dioxide ($CO_2$) and Carbon Dioxide Reducing Measure (CRM).

**LNG** Liquified Natural Gas (LNG) is natural gas (predominantly methane, $CH_4$) that has been converted to liquid form for ease of storage or transport. Natural gas is transported as LNG on LNG carriers but can also be used as a fuel, on all types of ship. See Boil-off Gas (BOG).

**MACC** A Marginal Abatement Cost Curve (MACC) is a way of representing options to reduce Carbon Dioxide ($CO_2$) emissions, or selecting Carbon Dioxide Reducing Measures (CRMs). The width of each bar represents the potential of the measure to reduce Carbon Dioxide ($CO_2$) emissions compared to a baseline scenario (normally carrying on with business as usual and taking no action). The height of each bar represents the average marginal cost of avoiding 1 tonne of $CO_2$ emissions through that measure, assuming that all measures to the left are already applied. The effect of the remaining measures decreases as one measures is implemented and it is assumed that the most cost-effective measures are implemented first. See Carbon Dioxide Reducing Measures (CRMs).

**main engine** The main engine is normally the primary source of the power used for propulsion. This arrangement is applicable for most mechanically driven arrangements where the propeller shaft is connected to a engine (normally via a gearbox), though not applicable to some arrangements, such as if the propulsion system is driven by electric motors. For most cargo ships auxiliary power is provided by a set of generating sets that is separate from the propulsion engines. See Auxiliary Power.

**MARPOL Annex VI** In 1997 a new annex was added to the International Convention for the Prevention of Pollution from Ships (MARPOL). The Regulations for the Prevention of

Air Pollution from Ships (MARPOL Annex VI) seek to minimise airborne emissions from ships and their contribution to global air pollution and environmental problems. See Marine Environment Protection Committee (MEPC) [`http://www.imo.org`].

**MBM** Market-Based Measures (MBMs) are policy instruments that use price and other variables related to economic incentive. MBMs seek to address the market failiure of pollution. Taxing Carbon Dioxide ($CO_2$) emissions is a MBM. A alternative approach is command and control approach, such as equipment having to meet a certain emission specification. The Energy Efficiency Design Index (EEDI) is a command and control approach.

**MCR** Maximum Continuous Rating (MCR) is defined as the maximum output that a engine is capable of producing continuously under normal conditions. Normally ships and their propellers are designed to operate at their design speed between 75% and 90% MCR with a margin for weather, fouling and wear. See main engine and design speed.

**MEPC** The Marine Environment Protection Committee (MEPC) is a committee of the International Maritime Organisation (IMO). The committee develops international conventions relating to marine environmental concerns including ship recycling, control of emissions and protection of marine life. See Regulations for the Prevention of Air Pollution from Ships (MARPOL Annex VI) [`http://www.imo.org`].

**$NO_x$** Nitrogen Oxides ($NO_x$) are a by-product normally from using fossil fuels created from the Nitrogen in the air. Emission Control Areas (ECAs) and Ports may place more strict regulations on $NO_x$ emissions. See Emission Control Areas (ECAs) and Selective Catalytic Reduction (SCR).

**operational speed** A ship's operational speed is associated with a percentage of the Main Engine Maximum Continuous Rating (MCR). Reducing operational speed is a short-term Carbon Dioxide Reducing Measure (CRM) that can be implemented quickly although reducing operational speed can move a ship further from the ship's design condition and is termed slow steaming. Sometimes used interchangeably with design speed, but not to be confused with design speed. See Carbon Dioxide Reducing Measure (CRM), Main Engine, Maximum Continuous Rating (MCR), design condition, slow steaming, speed and design speed.

**Panamax** Panamax and New-Panamax are terms for the size limits of ships travelling through the Panama Canal. The limits reuirements are published by the Panama Canal Authority. Panamax dimensions have influenced the design of cargo ships that are required to transit the canal since the opening of the canal in 1914. Ships that are larger than the Panamax size are called Post-Panamax. A New-Panamax size will be in effect from 2015, when a third lane of locks becomes operational. This will increase the Panamax beam from 32 metres to 49 metres [`http://pancanal.com`].

**PM** Particulate Matter (PM) is tiny pieces of solid or liquid matter. In the context of this work, PM is normally derived from the combustion of fossil fuels. PM from fossil fuels may include impure carbon particles, soot, resulting from the incomplete combustion of hydrocarbons.

**reefer container** A reefer container is a type of shipping container designed for the refridgeration or freezing of goods, normally produce. Reefer containers are normaly either 20 or 40 foot long standardised shipping containers. Reefer containers are fitted with a refridgeration unit and therefore have to be well ventilated and have to be connected to reefer sockets onboard the ship for power. See TEU.

**retrofit** A retrofit is to add a component or accessory to an existing ship that did not have it when manufactured, normally as a Carbon Dioxide Reducing Technology (CRT). Retrofits are limited to minor changes and are unlikely to incorporate a wide range of single and multiple CRTs compared to a new build. See Carbon Dioxide Reducing Technology (CRT) and new build.

**SCR** Selective catalytic reduction (SCR) is a means of converting nitrogen oxides $NO_2$ with the aid of a catalyst into diatomic nitrogen ($N_2$) and water ($H_2O$).

**SEEMP** The purpose of a Ship Energy Efficiency Management Plan (SEEMP) is to establish a mechanism for a company and/or a ship to improve the energy efficiency of a ship's operation. The SEEMP seeks to improve a ships energy efficiency through four steps: planning, implementation, monitoring, and self-evaluation and improvement. At the 62nd MEPC meeting at the IMO in July 2011 it was agreed that the Energy Efficiency Design Index (EEDI) will become mandatory for new ships as well as the Ship Energy Efficiency Management Plan (SEEMP) for all ships over 400 gross tonnage. Expected to enter into force on 1 January 2013 and added to Regulations for the Prevention of Air Pollution from Ships (MARPOL Annex VI). See Regulations for the Prevention of Air Pollution from

Ships (MARPOL Annex VI) and Marine Environment Protection Committee (MEPC) [Marine Environment Protection Committee - Circ.683].

**shipping system** The shipping system is used to refer to all the stakeholders that may effect the calculation of carbon dioxide emissions of a ship with different Carbon Dioxide Reducing Technology (CRTs) combinations. This could include consideration of economics and operations or infrastructure considerations. For example, though on a single ship level a change in fuel may be an effective way to reduce Carbon Dioxide ($CO_2$) emissions the option may not be viable if the port and infrastucture of the shipping system does not supports the fuel. Naval Architects and Marine Engineering should consider these wider aspects in design.

**shipping system model** The shipping system model is the economic model of international shipping that is used in the Low Carbon Shipping (LCS) project to select the most appropriate technologies according to market conditions and regulatory constraints. The shipping system model consider economin and logistical aspects of the shipping market such as trade flows, demand and supply and different energy scenarios and uses a database of Carbon Dioxide Reducing Technologies (CRTs) based on the outputs from the Ship Impact Model (SIM).

**SIM** Model that models the primary impact, assumes Carbon Dioxide Reducing Technologies (CRTs) impact on cargo, of one or more Carbon Dioxide Reducing Technologies (CRTs) on a certain cargo ship type, size and design speed over an operational speed profile. The Ship Impact Model (SIM) does not involve an iterative design process and does not consider layout issues. A Detailed Ship Model (DSM) is used alongside the SIM to check the results by considering a full ship design. The SIM is modelled in Matlab. See Carbon Dioxide Reducing Technology (CRT), cargo ship, design speed, operational speed profile and Detailed Ship Model (DSM).

**$SO_x$** Sulphur Oxides ($SO_x$) are a by-product normally from using fossil fuels created from the sulphur in the fuel. Some fuels used in shipping, such as Heavy Fuel Oil (HFO) may have a high sulphur content. Emission Control Areas (ECAs) and Ports may place more strict regulations on $SO_x$ emissions. See Emission Control Areas (ECAs).

**TEU** A Twenty-foot Equivalent Unit container is a 20 foot long standardised shipping container that is used to transport a variety of goods and sometimes as a measure of ship capacity. 40 foot containers are at least as common as 20 foot containers and a variety of other sizes and configuration are also used, such as 45 foot containers, high height containers and more specialist containers, though all containers share the same twislock fittings in the corners and are of the same width. See reefer container.

**TLC** Through-Life Cost (TLC) is the average annual cost directly associated with the use of a Carbon Dioxide Reducing Technology (CRT). This could include additonal maintenence costs or crewing costs.

**TRL** Technology Readiness Level (TRL) is an indication of how close a technology or product is to being safely applied/used. Low TRLs need both additional investment/resources to be developed and may be at risk from not being viable. High TRLs need little investment and can be applied quickly. TRLs are mainly used to describe how close to Carbon Dioxide Reducing Technologies (CRTs) are to becoming commercially available on the market. TRL definitions were initially developed by NASA. See Cabon Dioxide Reducing Technology (CRT).

**UNFCCC** The United Nations Framework Convention on Climate Change (UNFCCC) is an International treaty that initially took effect in 1994 and has the ultimate aim of preventing "dangerous" human interference with the climate system. The UNFCCC works to limit average global temperature increases and cope with the resulting impacts of climate change and also directs funds to climate change activities in developing countries. See Kyoto Protocol [http://unfccc.int].

**UPC** Unit Puchase Cost (UPC) is all the costs associated with the installation cost of a Carbon Dioxide Reducing Technology (CRT), where applicable this includes labor and supporting infrastructure costs, such as dry-docking, as well as equipment costs. See Carbon Dioxide Reducing Technology (CRT) and Through-Life Cost (TLC).

**WSM** The Whole Ship Models (WSMs) are full three-dimensional early stage ship design model that has the purpose of accurately representing specific commercial ship types. The WSMs are partially parametric (they are not fully parametric because it is necesary to avoid losing design detail). The WSMs have to respond accurately to changes to the ship due to Cabon Dioxide Reducing Technologies (CRTs). The WSMs are in the ship design software Paramarine.